AN ASSESSMENT OF ROCKFALL ACTIVITY USING DENDROGEOMORPHOLOGY: THE AMPHITHEATER, OURAY, COLORADO, USA

A Thesis

by

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ABSTRACT

A U.S. Forest Service campground and adjacent hiking trails are subjected to rock-fall activity from a nearby bedrock escarpment. The campground is situated in a glacial-carved valley of the Ouray, Colorado, Amphitheater in the San Juan Mountains. A dendrogeomorphic assessment of the trees and steep slopes surrounding campground investigate the past and present stability conditions to answer the question: What are the spatial and temporal characteristics of rock fall? More specifically, for this area, where spatially is the slope subjected to rockfall activity and what are the magnitude and frequency of events? Also, will reconstructing a rockfall chronology using a dendrogeomorphic methodology of *Abies concolor* (White fir) help identify potential triggering mechanisms? To answer the research questions, the following two objectives were established for this study: (i) delineate the spatial patterns of rockfall activity, and (ii) establish a temporal chronology of rockfall activity. The spatial extent of rock-fall activity is assessed by mapping areas of talus accumulations and trees exhibiting visual evidence of rock-fall activity. Visible rock-fall induced tree disturbances observed in the study area include: impact scars, tree decapitation, curved or leaning trees, and elimination of neighboring trees or 'broken crown'. The area with the greatest hazard to rockfall activity is the area located below the gullies of the overlying cliffs and steep slopes, the scree slopes below the base of the cliff, and for ~70 m into the forest from the upper protective forest boundary and ~100 m from the base of the cliff. 'Centurion' trees are the most likely to record a growth defect as result of rockfall activity. The sampling

of selected trees with an increment borer allowed for microscopic analysis of the variations of tree-ring width measurements as a trees response to rock-fall induced growth defects (GD) (reaction wood, suppression and release, and cellular scaring/callus tissue). The initiation, duration, and termination of the growth defects (GD) allowed for the reconstruction of a rock-fall chronology. This reconstruction alluded to the observation of rockfall activity being dominated by low magnitude, high frequency events, and interpreted as being attributed to annual freeze and thaw activity. For the time period of investigation (1910-2015), no large mass movement event occurred within the study area. Although there were no observations of a large-scale mass movement event, several years recorded abnormally high rockfall rates, as determined from the reconstructed rockfall chronology. Years with abnormal rockfall rates are a result of some additional external factor ‘promoting’ and/or ‘triggering’ the rockfall event.

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CHAPTER I

INTRODUCTION

Every summer, thousands of people visit the many national, state and city parks of Colorado to experience the beautiful outdoors and natural wonders that are present. For those who venture into the mountainous terrain of southwestern Colorado, they might experience some of the natural hazards that are present in the area, including steep topography and the potential for mass movement events. One of the common types of mass movement is rockfall. The steep slopes and cliffs of the San Juan Mountains of are prime locations for rockfall activity. Glacial-carved valleys have created steep slopes and cliffs that have been exposed to significant weathering, creating potentially isolated areas of instability. Hiking trails and campgrounds are often located in these areas because of their scenic beauty and access to recreational spots. Unfortunately, this places them in areas vulnerable to mass movement hazards, specifically rockfall.

State, county and city official have long recognized rockfall as a hazard and, thus, they require current research thinking to recognize and monitor new hazardous areas: rockfall can cause significant losses to life and property (CDEM, 2013). The 2013 Colorado natural hazards mitigation plan reported more than $3 million in damages and five deaths resulting from landslide and rockfall activity (CDEM, 2013). Identifying areas of rockfall activity and understanding the driving forces allows state and city officials to not only plan for safety, but also promote public awareness of the hazard of rockfall activity and its associated risks. A study of rockfalls can also lead to preventative mitigation in necessary areas.

Many methodologies (Luckman and Fiske, 1995; Nesje et al., 1994; Bjerrum and Jorstad, 1968; Douglas, 1980; Andrew, 1994) exist to actively study the processes associated with rockfall; however, the most accurate method for dating rockfall activity when a log or record of activity is absent, is the analysis of impacted or disturbed trees and their associated growth response recorded in the tree-ring record (Schneuwly et al., 2009). This process is known as dendrogeomorphology (Alestalo, 1971). The goal of this thesis was to integrate dendrogeomorphic techniques with standard geomorphic practices to develop a record of the rockfall activity as well as an understanding of the processes responsible for activity on the steep slopes adjacent to the US Forest service campground in the Ouray area. The research from this thesis confirms the use of tree-ring analysis of *Abies concolor* (White fir) to be an effective tree species for rockfall analysis.

1.1 Background and Problem Statement

Ouray, is located in one of the many glacial-carved valleys of the Western San Juan Mountains of southwestern Colorado (figure 1). Adjacent to the southeastern side of Ouray is a U.S. Forest Service campground, which is situated within a large amphitheater.

The topography within the Amphitheater consists of multiple mass movement deposits, which have created 7.62 million m^2 (~82 million ft^2) of 'landslide deposits (APPENDIX B1). Composed of San Juan tuff mixed with glacial deposits of Pleistocene age, the deposits are presently 'inactive' (Reed, 2013). Reed (2013) argues that Zaruba and Mencl (1982) are incorrect in classifying such deposits as relict. However, such

deposits, like the amphitheater deposits, cannot be relict, as they are either active or inactive. A landform can be relict, but not a process. Classification of this 'inactive state' for the deposits is supported by widespread vegetation cover on the deposits, as well as intermittent lines of drainage that extend across the landslide (Skempton and Weeks, 1976).

Reed (2013) provides a preliminary analysis of the extent and mechanism of the large amphitheater landslide; however, the occurrence of curved and leaning trees, impact scaring of trees, and steep slopes of alluvium/talus indicating unstable slope conditions surrounding the forest service campground and field observations suggest evidence for additional slope-instability conditions involving soil creep, avalanche debris, debris flows, rockfalls and rock slides all of which suggest further study is needed. This leads to the question: could thesis trees hold the key to understanding rockfall activity in this area?

The research of this thesis focused on the rock-fall activity occurring along the rock face around the upper circumference of the deposit. Injured and disturbed trees occur on the deposit as result of rockfall activity (APPENDIX B2). These scarred trees provide the opportunity to employ dendrogeomorphology in conjunction with standard geomorphic techniques to create a temporal and spatial assessment of rockfall activity and associated hazards.

The problem can be stated as: What are the spatial and temporal characteristics of rockfall? More specifically, for this area, where spatially is the slope subjected to rockfall activity and what are the magnitude and frequency of events? Also, will

reconstructing a rockfall chronology using a dendrogeomorphic methodology of *Abies concolor* (White fir) help identify potential triggering mechanisms?

1.2 Objectives

The following two objectives have been established for this study:

(i) delineate the spatial patterns of rockfall activity and

(ii) establish a temporal chronology of rockfall activity.

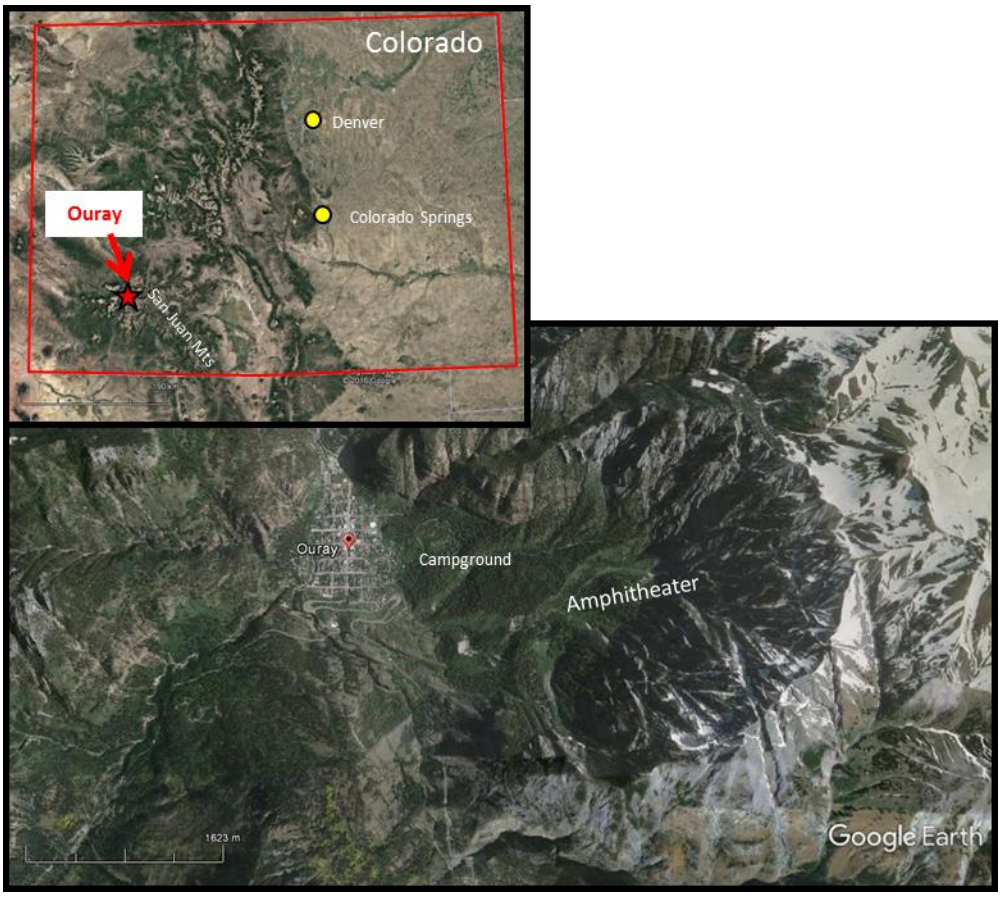

Figure 1 Study area is located in the San Juan Mountains of southwestern Colorado, east of Ouray (Google)

CHAPTER II

LITERATURE REVIEW

A literature review provides the necessary background information regarding the fundamentals of rockfall. Topics covered with this literature review include the causes of rockfall, rockfall movement, rockfall modeling, rockfall hazard assessment, and dendrogeomorphology.

2.1 Rockfall Fundamentals

2.1.1 Causes of Rockfall

Rockfall differs from other mass movement processes, in that rocks "free fall" as a result of gravity. Ritter et al.,(2002) defines rockfall as:

A single mass that travels as a freely falling body with little or no interaction with other solids. Movement is normally through the air, although occasional bouncing or rolling may be considered as part of the motion (Ritter et al. 2002 pg 105).

Rockfall begins with the detachment of a rock or rocks from a bedrock slope or cliff. All slopes have pre-existing morphological, geological, and geotechnical properties and are subjected to various degrees of physical and chemical weathering (Lee et al., 1997). For each slope, the pre-existing conditions, such as rock strength, degree of jointing, or crack presence can lead to the promotion of rockfall (Farran and Thenoz, 1965; Whalley, 1984; Dorren, 2003; Schneuwly, 2009). Therefore, the detachment of a rock from a slope is distinguished by the "promoter", which may lead to favorable conditions for movement, and the "trigger", or the mechanism that causes the actual start of movement.

There are many triggering mechanism that could lead to rockfall, however, in many cases, the rockfall promoter and trigger can be addressed together such as with the process of frost-thaw activity (Schumm and Chorley, 1966; Porter and Orombelli, 1981; Dorren, 2003; Matsuoka, 2008; Schneuwly, 2009). Alternating cycles of freezing and thawing, in conjunction with moisture can promote further weathering and cause the detachment of rockfall. When moisture or water, known as cleft water, within the intergranular void space ("primary porosity" associated "primary permeability") begins to freeze; joints, cracks, and fissures will form as the volume increases (Terzaghi, 1962; Farran and Thenoz, 1965; Schumm and Chorley, 1966). "Secondary permeability" is the space between cracks and fissures. Repeat cycles of temperature increase and subsequent ice melting further widen of the cracks. The frequency and size of rockfall is controlled by the crack morphology and governed by the rock's permeability, strength and proneness to failure (Farran and Thenoz, 1965; Ishikawa et al. 2004; Schneuwly, 2009). The scale at which freeze-thaw action propagates cracks in rocks will determine the size of the material that falls. Also, cracks in rocks and subsequent removal of finer material may cause vertical stacking which relies on the frictional component of the rock type (Hofmann, 1974). Further instability can be caused by the presence of expansive clays within the cracks and joints, that when wet, create a frictionless sliding plane (Barton and Choubey, 1977).

Rockfall caused by alternating freeze-thaw cycles are generally low magnitude, high frequency events (Matsuoka and Sakai, 1999) and are controlled by the geological, geotechnical, and morphological character of the cliff and surface temperature

fluctuations (Luckman, 1976; Douglas, 1980; Dorren, 2003). The effects of the micro-scale activity, such as water content or the rate and intensity of freezing will be greater on cliffs composed of rocks with higher porosity and permeability (Whalley, 1984).

Water in the form of rapid snowmelt can also trigger rockfall when increasing temperature begin to melt large amounts of ice and snow, outside of freeze-thaw cycles, filling the cracks and joints and increasing pore pressure (Schneuwly, 2009). In the absence of freeze-thaw cycles, rockfall can be triggered by extreme meteorological events, such as heavy rainfall, winter storms, and wind storms (Dorren, 2003). While there is potential for rockfall to have only one trigger, often rockfall is triggered by a combination of two or more factors of frost-thaw action, rapid melting, and heavy rainfall (Nyberg, 1991; Schneuwly, 2009).

Other processes known to trigger rockfall include earthquakes (Bull and Brandon, 1998; Bull, 2004), root penetration and wedging (Wieczorek et al., 1995, 2000), and chemical weathering (Carson and Kirkby 1972). Chemical weathering alters the rock strength, promoting rockfall release by exogenic processes: thermal effects of granular disintegration, salt crystallization, and chemical weathering of weaker minerals (Carson and Kirkby 1972; Whalley, 1984; Matsuoka, 2008).

When common triggers such as precipitation, seismic activity, and freezing conditions are absent, cyclic and cumulative deformation of exfoliation sheets can trigger rockfalls from the thermal heating and expansion of rock surfaces (Coutard and Francou, 1989; Gunzburger et al., 2005; Collins and Stock, 2016).

Finally, human activity can destabilize rock slopes through equipment vibrations, undercutting of slopes for roads, or loading from infrastructure (Giardino, in review). In addition, humans and animals can detach loose rocks when climbing steep cliffs or slopes (Dorren, 2003).

2.1.2 Rockfall Movement

Rockfall analysis investigates the objective 'hazard' of the rockfall itself, and the associated 'risk'. Hazard and risk are often used interchangeably, even though they do not have the same meaning. The 'hazard' is the source of potential danger associated with rockfalls, and includes aspects of the slopes geology and geomorphology (Varnes, 1978; White and Wait, 2008). 'Risk' is the chance or probability of rockfalls interacting or causing damage to human life or property (Schuster R. L., 1978; Ritter, 2001; White and Wait, 2008).

The initial detachment of a rock fragment is called "primary removal". Resting material that begins to move after its original weathering, when heavy rain or snowmelt creates a mechanism for material transport is called "secondary removal" (Luckman, 1976; Whalley, 1984). A detached rock descending a slope is distinguished by different modes of motion, which mainly depends on the mean slope gradient. The three main modes of motion are freefalling, bouncing and rolling on a slope (figure 2).

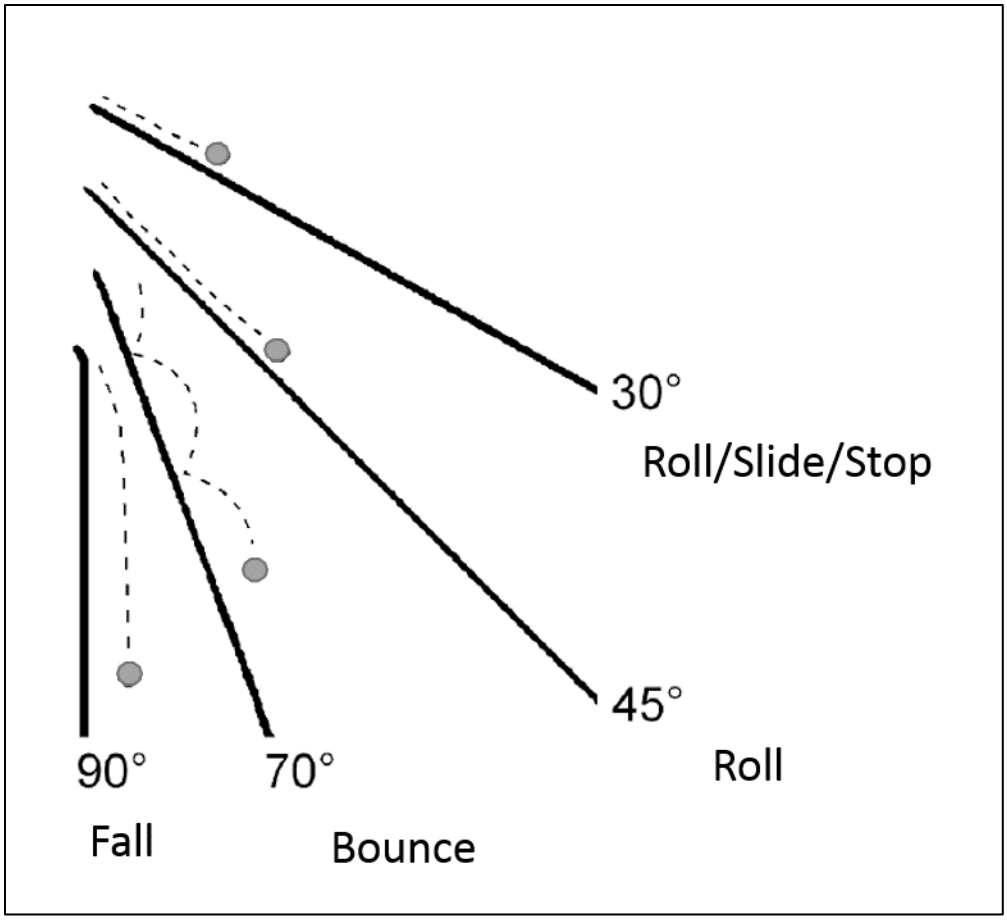

Figure 2 Rockfall modes of motion along a slope in relation to the mean slope gradients (modified from Dorren, 2003)

The location and type of movement of a rockfall on a slope is divided into three zones of the departure zone, transit zone, and deposition zone (Dorren, 2003; Schneuwly, 2009) (figure 3). The point where a rock fragment detaches from the slope is called the departure zone. A cliff slope of 70° is needed for a rock to fall (Dorren, 2003). A falling rock's initial impact with the surface of a slope is defined as a bounce and will generally break up into smaller pieces (Bozzolo and Pamini, 1986). The first impact will lose 75-86% of the initial energy gained from falling and is related to slope rock

hardness, slope saturation, and degree of loose material (Evans and Hungr, 1993). When the angle of a slope decreases to 45°, a bouncing rock will accumulate rotational energy and begin rolling. A rock will continue to lose energy as it descends a slope. The transit zone is the middle part of the slope where no primary removal occurs below the departure zone (Schneuwly, 2009). Rockfall material is 'passing through' the transit zone as the slope angle is too high for permanent storage. Resting material in the transit zone can be reactivated as secondary removal and continue down slope. When a rock comes to rest, it is deposited in the deposition zone, typically where the slope flattens to an angle of 30° (BUWAL et al., 1997). The exact critical angle however, is dependent on the rock shape (Azzoni et al., 1995).

The runout distance depends on the mean slope gradient, rock size, and slope cover (soil, talus/scree, and vegetation) (Azzoni et al., 1995). Larger rocks will tend to travel farther because they will have a higher kinetic energy than smaller rocks, which are more likely to be stopped by trees and large boulders (Dorren, 2003). Because of this, rockfall slopes will show evidence of clast sorting with smaller material depositing at the base of the cliff as a talus slope and larger boulders further down slope. On alpine slopes, large boulders may also be transported further down slope by avalanches so the boulder size and talas slope/ forested interaction should be carefully considered (Schneuwly, 2009).

The stopping of a rock is a process through which energy is lost through collisions and by friction. Friction is the result of rock shape and slope surface characteristics (BUWAL et al., 1997; Azzoni et al., 1995; Dorren, 2003). The friction

component is realized using the dynamic angle of friction (Kirkby and Statham, 1975) and the surface roughness (Chang, 1998; Andrew et al., 2012).

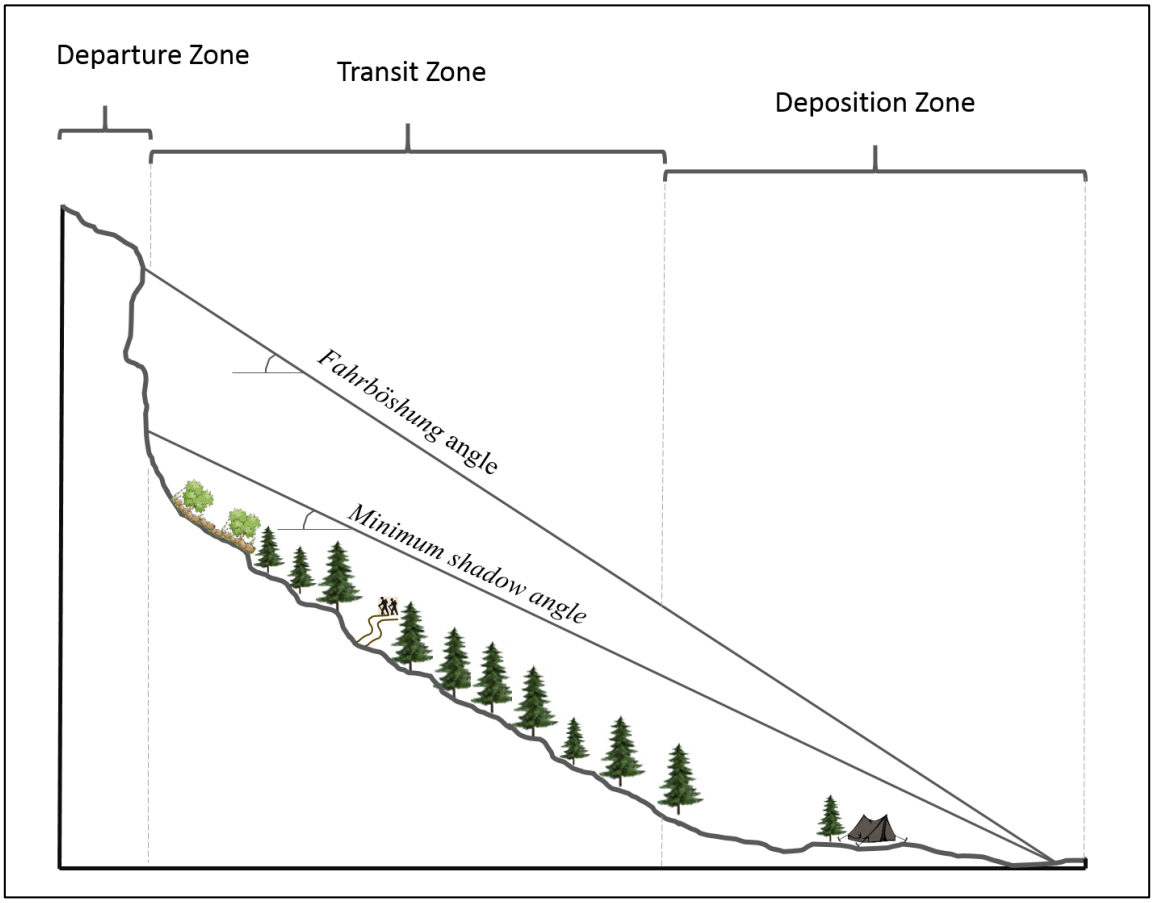

Figure 3 Schemmatic diagram of the Ouray rockfall slope under investigation subdivided into departure, transit and deposition zone with graphical representation of the "Fahrböshung angle" and the "minimum shadow angle" (modified after Buwal et al., 1997; Dorren, 2003; Schneuwly, 2009)

Experimental studies (BUWAL, 1997; Azzoni and Rossi, 1991) and reconstructions (Rickli et al., 2004; Dorren et al., 2006) suggest rockfall material could have average velocities ~ 11 ms^{-1} (~36 fts^{-1}), maximum velocities ~30 ms^{-1} (98 fts^{-1}), and

large boulders reaching rebound jump distances of ~30 m (~98 ft) and average heights of 1.5 m (5 ft), max. 8 m (26 ft).

Rockfall movement tends to be most frequent along the gullies of steep slopes (Whalley, 1974). Gullies and large cracks originate from 'residual' stresses in the mountain as a result from orogenic activity (Hast, 1969). Gullies collect rain and snowmelt as a channelized flow and isolating the erosive force of the water to a limited area. The collected water also saturates into the surrounding rocks inducing increased weathering, specifically suitable for freeze-thaw conditions. Because of this, primary removal/rockfall is more likely in gullies. In addition, gullies provide and collect small talus material which can be activated or reactivated as secondary removal from the rockfall impact of previously weathered rocks (Caine, 1974; Whalley, 1984). Thus, rockfall activity in gullies are frequent and provide an abundance of small talus material down the steep slope. In contrast, buttresses are much larger and rarer falls due to the complex nature of the forces and stresses applied to the rock slope (Hast, 1969; Whalley, 1984).

2.1.3 Rockfall Modeling

Rockfall modeling of calculating runout zones began as a way to satisfy the general principle of hazard mapping procedure: a) determine the location of the hazard potential and departure/release zones, and b) estimate maximum run-out distances (Berger and Dorren, 2006; Berger et al., 2013). The differing models aim to understand how falling rocks move along a slope and estimate run-out distances. The three most

common methodologies for rockfall modeling include empirical models, process-based models and GIS-based models (Dorren, 2003; Berger et al., 2013)

Empirical methods are commonly used for identifying potential release and propagation zones based on the relationships between topographical factors and maximum rockfall run-out distances (Dorren, 2003; Berger et al., 2013). Probabilistic empirical models use analysis of past databases (Berger and Dorren, 2006). Heim (1932) introduced the *Fahrböshung* angle, or the Energy Line Angle (ELA) which states: for any rockfall, there is a specific slope angle between a horizontal plane and a straight line that connects the top of the rockfall source to the stopping point (figure 3). Evans and Hungr (1993) proposed the *minimum shadow angle* as an alternative method. The *minimum shadow angle* is the angle between a horizontal plane and a straight line connecting the point where the base of a cliff intercepts a talus slope and the longest run-out boulder (figure 3). Evans and Hungr (1993) suggests a *minimum shadow angle* of 27.5° for maximum rockfall run-out distances.

In addition to empirical methods, process-based methods model the modes of motion along a slope surface (Dorren, 2003). With the advent of modern technologies, these empirical and process-based methods can be simulated rockfall motion and its interaction with the slope surface in three-dimensional space (GIS-based models). GIS-based models identify the source area, determines the falltrack, and calculates the run-out zone (Hegg and Kienholz, 1995).

2.2 Hazard Assessment

The hazard analysis and risk assessment of rockfall has received increased interest over the last couple decades. A successful hazard assessment will investigate: the special extent of where rockfall occurs, rock-fall frequency and magnitude, and potential triggering mechanisms (Schneuwly, 2009).

Many techniques have been applied to gather data assessing rock fall activity. Lichenometry is used to compare lichen size to annual growth rates (Luckman and Fiske, 1995). Lichenometry assumes the largest lichen growing on a surface is the oldest. Thus, if growth rates are known, the minimum age of when a rock was deposited can be estimated from the maximum lichen size (Bull and Brandon, 1998, Bull, 2004, Porter and Orombelli, 1981). Mapping and dating of rockfalls by studying lichen growing on the surface of boulders and talus has been successfully carried out by (Hale, 1967; Carrara and Andrews, 1973; Porter and Orombelli, 1981; Luckman and Fiske, 1995; Bull and Brandon, 1998; Bull, 2004).

Nesje et al. (1994) used another method in dating rockfall deposits byidentifing unique weathering indicators as a response to hammer impact. Others such as Bjerrum and Jorstad (1968) and Douglas (1980) measured qualitative and quantitative results of rockfalls by collecting fallen material on large tarps or blankets and recording rock type, size, and distribution of size over a set period of time and statistically applying a variable mean in monthly increments over the course of a year.

In recent years, dendrogeomorphic techniques have been applied in rockfall reconstructions to establish specific rockfall rates (Stoffel et al., 2005b; Stoffel & Bollschweiler, 2008; Stoffel, 2006; Schneuwly et al., 2009).

As a result of roads being constructed in areas of steep terrain where rockfall is common, many local and state governments have developed hazard rating systems to assess the local hazardous conditions of roadways and populous areas. The Colorado Department of Transportation (CDOT) developed the Colorado "Rockfall Hazard Rating System" or "RHRS" (Andrew, 1994; modified by Russell, 2005; Russell et al., 2008). This approach ranks the dominating factors (geology, slope morphology, rockfall volume or triggering factors) that contribute to rockfall (table 1) and categorizes rock slopes to produce an overall hazard rating (Patrick and Manitou-Alvarez). The Colorado RHRS was originally designed to assess the rockfall hazards to roads and state highways. Authors such as (Guzzetti et al., 2003; Jaboyedoff and Labiouse, 2003; Patrick and Manitou-Alvarez) have modified these rating systems to emphasize the hazards associated with the slope, climate, and geological characteristics.

Table 1 The Colorado Department of Transportation (CDOT) "Rockfall Hazard Rating System" or "RHRS" (from Russell, 2005)

Colorado Rockfall Hazard Rating Field Worksheet

Sight Information				
ROUTE NO	SEGMENT ID NUMBER	ENGINEERING REGION	MAINTENANCE SECTION	DATE
COUNTY	BEGIN MILE POST	END MILE POST	R, L OF CENTERLINE	RATER

Actual Values		*Remarks*
Slope Height _____	Ditch Depth _____	Major rockslide potential:
Slope Angle _____	Sight Distance _____	Dominating rockfall mode: Block-in-matrix / Sedimentary rock / Crystalline rock
Ditch Slope _____	Speed Limit _____	Dominating sight distance: Horizontal / Vertical
Ditch Width	ADT	Mitigation effectiveness: A B C D F

Rating	Cut Slope / Total Slope (Circle one)		3 Points		9 Points		27 Points		81 Points
Slope	Slope Height		25 to 50 ft		50 to 75 ft		75 to 100 ft		>100 ft
	Rockfall Frequency		> 2 years		1 to 2 years		Yearly, seasonal		Year round / severe events
	Average Slope Angle Score		0 to 2		2 to 4		4 to 8		> 8
	Launching Features		None (smooth slope)		Minor (< 2 ft. surface variation)		Many (2 to 6 ft. surface variation)		Major (> 6 ft. surface variation)
	Ditch Catchment		95% to 100% / Class 1		65% to 94% / Class 2		30% to 64% / Class 3		< 30% / Class 4 / ≥ Major launching features
Climate	Annual Precipitation		< 10 inches		10 to 20 inches		20 to 35 inches		> 35 inches
	Annual Freeze Thaw Cycles		1 to 5		6 to 10		11 to 15		16 or more
	Seepage / Water		Dry		Damp / wet		Dripping		Running water
	Slope Aspect		N		E, W, NE, NW		SE, SW		S
Geology	Sed. Rock	Degree of Under-Cutting	0 to 1 ft		1 to 2 ft		2 to 4 ft		> 4 ft
		Jar Slake	6		5		3 to 4		1 to 2
		Degree of Interbedding	1 to 2 weak interbeds, < 6 in.		1 to 2 weak interbeds, > 6 in.		> 2 weak interbeds, < 6 in.		> 2 weak interbeds, > 6 in.
	Crys. Rock	Rock Character	Homogencus / massive		Small faults / strong veins		Schist / shear zones < 6 in.		Weak pegmatite / micas / shear zones > 6 in.
		Degree of Overhang	0 to 1 ft		1 to 2 ft		2 to 4 ft		> 4 ft
		Weathering Grade	Fresh		Surface staining		Slightly altered / softened		Core stones
	Discontinuities	Block Size / Volume	<1 ft / <1 cy		1 to 2 ft / 1 to 3 cy		2 to 5 ft / 3 to 10 cy		>5 ft / >10 cy
		Number of Sets	1		1 plus random		2		> 2
		Persistence, Orientation	< 10 ft and dips into slope		> 10 ft and dips into slope		< 10 ft and daylights out of slope		> 10 ft and daylights out of slope
		Aperture	Closed		0.1 to 1 mm		1 to 5 mm		> 5 mm
		Weathering Condition	Fresh		Surface staining		Granular infilling		Clay infilling
		Friction	Rough		Undulating		Planar		Slickensided
	Block in Mat.	Block Size (x3)	< 1 ft		1 to 2 ft		2 to 5 ft		> 5 ft
		Block Shape (x3)	Tabular		Blocky		Blocky to angular		Rounded and smooth
		Vegetation (x3)	Fully vegetated		Patchy vegetation		Isolated plants		None
Total Hazard Score:									
Traffic	Sight Distance		> 80 %		60 % to 80 %		40 % to 60 %		< 40 %
	Avg. Vehicle Risk		0 to 24%		25 to 49%		50 to 74%		75% or more
	No. of Accidents		0 to 2		3 to 5		6 to 8		9 and over
Total Risk Score:									

Additional Rater's Comments:

CHAPTER III

STUDY AREA

This chapter provides an overview of the investigated study area; the location of the study site; how to access the site; and an overview of its geology, geomorphology, climate, and vegetation.

3.1 Study Area

The study area is located ~2.4 km (~1.5 miles) northeast of the town of Ouray, (38°1′24″N,107°40′20″W) Colorado, United States (figure 1). The study area encompasses the National Forest Service campground at an elevation of 2,580 m (8,470 ft).

Access to the study area from Ouray, CO, is provided by county road 16 off of State Highway 550. The investigated forest, as outlined by the thin dashed line in figure 4 is located between 2,560 and 2,660 m (8,400 and 8,730 ft) elevation northeast of the campground and has an area of 43,500 m^2 (468,230 ft^2).

3.2 Geology and Geomorphology

The steep slopes surrounding the campground is covered by Quaternary talus overlying Pleistocene landslide material composed of San Juan tuff mixed with glacial deposits. Talus material is derived from the nearby bedrock escarpment composed of Pennsylvanian – Tertiary sediments (figure 5, figure 6). The entire study area noted by the bolded dashed line of figure #, which inclides all departure and deposition zones, covers ~ 325,500 km^2 (3,501,527 ft^2).

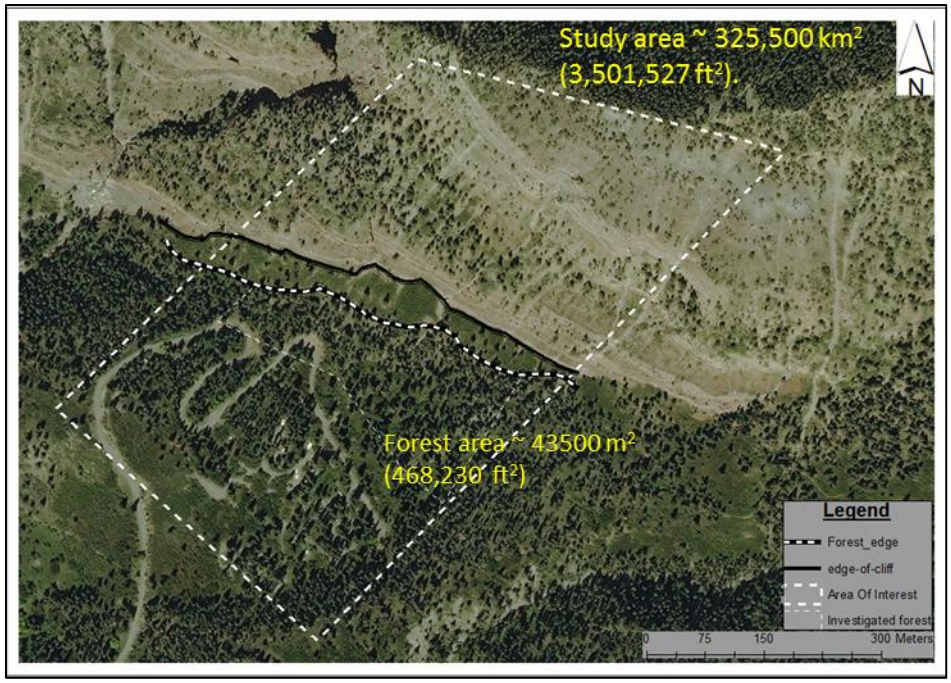

Figure 4 Study area is located in the San Juan Mountains of southwestern Colorado, east of Ouray, as denoted by bold black dashed line

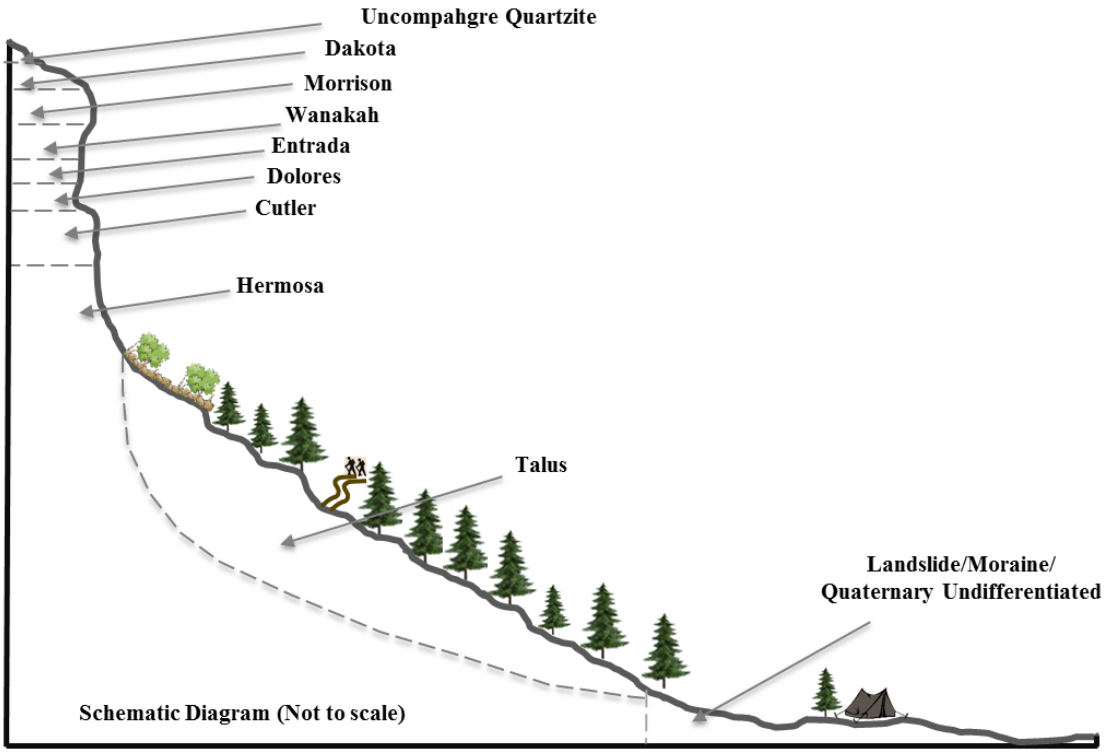

Figure 5 Schematic diagram illustrating key slope components

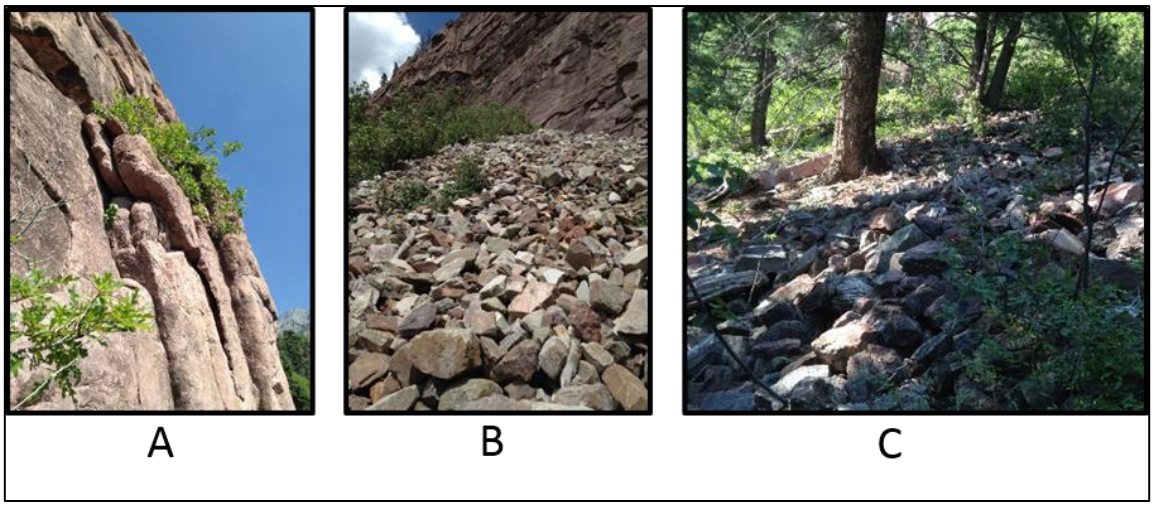

Figure 6 (A) Fractured Sandstone and interbedded limestone and shale cliff is the source of the rockfalls; (B) Talus buildup into steep slopes; (C) Vegetated slopes acting as a protective forest to falling debris (Photos by Author)

Rocks are being detached from a ~430 m (~1,400 ft) thick section of intervening cliffs, slopes and ledges of various sedimentary lithologies (figure 5; figure 6; figure 7, figure 8) (Cross et al., 1907; Luedke and Burbank, 1962; Franczyk, 1993; Luedke and Burbank, 1994). The base of the cliff/talus slope is ~80 m (~260 ft) of cliff forming massive red-pink gritty channelized-sandstone, siltstone and shale of the middle member Pennsylvanian Hermosa formation (Ph). Also present are occasional interbedded thin red and gray fossiliferous shales and limestone. This unit has higher concentrations of feldspathic and conglomeritic sandstones and micaceous shales. The middle Hermosa is highly fractured providing evidence for differential weathering and possible frost-wedging (figure 6 A).

The upper Hermosa is ~90 m (~ 300 ft) thick and grades from greenish-gray ledges and cliffs of thin- to thick-bedded, red arkosic, coarse-grained sandstone and conglomerate to partially vegetated, scree slope conformable with the overlying Permian Cutler formation (Pc).

Within the study area, the Cutler is mostly identified as partially vegetated talus/scree slopes of the northeast and benches and cliffs to the southwest. The upper contact with the overlying Triassic Dolores formation (T_Rd) is an angular unconformity. The nearly 60 m (200 ft) thick section pinches out to zero to the east. Where exposed, the Cutler crops out as benches and cliffs of thin to massive bedded pink to reddish-brown shales, siltstones and sandstones. The Cutler also has conglomerate beds of pebbles and cobbles with very little interstitial material. Conglomerate material is

predominantly Precambrian metamorphic and igneous rocks as well as, limestone derived from the older underlying rocks.

The overlying Triassic Dolores formation crops out as 12-24 m (40-80 ft) of steep rubble covered slopes or cliffs and benches due to its variable lithology. The Dolores is composed of sandstone and siltstone with minor mudstones, limestones and conglomerates. The thin beds of sandstone are reddish-brown and the thick beds of massive sandstone are mottled red and white. The mudstone is reddish-brown, green and yellow and the limestones and reddish-brown conglomerates are on average .3 m (1 ft) thick.

The steep to rounded white cliffs above the Dolores is the Jurassic Entrada Sandstone formation (Je). The Entrada is a friable, calcareous, fine-grained quartz sandstone with thick to massive crossbedding. The sandstone is observed to be 12-24 m (40-80 ft) thick within the study area.

The entrada is overlaid by the Jurassic Wanakah formation (Jw) which crops out as a cliff in lower part and gentle to steep slopes in upper part. Luedke and Burbank (1962, 1994) broke this unit into three members: the lower limestone and breccia (Pony Express limestone member), a middle sandstone (Bilk Creek sandstone member), and an upper marl-mudstone (Marl member). The lower member is composed of thinly bedded dark gray/black limestone and interbedded black bituminous shale. The upper part of the Bilk Creek member contains nodular gypsum surrounded by dark black shale and porous breccia. The middle member contains greenish-gray, silty or fine grained, calcareous sandstone and greenish shales. The sandstone is very friable except where mineralized

and contains a thin resistive bed of greenish-gray medium grained sandstone with jasper grains that is common among the fallen talus and alluvium debris in the forest stand. The upper marl member is composed of thin-bedded, reddish-brown, calcareous mudstone-siltstone, interbedded with fine sandstones and nodular crystalline limestones. Much like the middle member, the upper Wanakah also contains a greenish bed of silty limestone with jasper grains and green chert. The Wanakah is 12-24 m (40-80 ft) within the study area.

The contact between the Wanakah and overlying Jurassic Morrison formation (Jm) is marked by a line of trees where the steep cliff grades into ledges, cliffs, and steep slopes partially covered by a soft layer of weathered rock and soil. The Morrison at this location is ~210 m (700 ft) thick and can be broken into two lithologic units, the lower Salt Wash sandstone member, and the upper Brushy Basin shale member. The lower Salt Wash is a fine to medium-grained sandstone with interbedded mudstones and the occasional limestone bed. Lenticular- and cross-bedding is common within the lower Salt Wash. Joint surfaces are sometimes covered by carbonates. The sandstones are yellowish white, yellowish brown and pink and in situ weathered surfaces are often covered in "bluish-black desert varnish". The number of mudstone layers and their thickness increase in the upper part of the Salt Wash member and grades into the upper Brushy Basin shale member. The Brushy Basin member is a calcareous mudstone with interbedded fine sandstones and limestones.

The Pack trail crosses the top of the ridge at ~3,078 m (~10,100 ft) through the slightly weathered cliffs of the Cretaceous Dakota Sandstone formation (Kd). The cliffs

have thin to massive lenticular, cross-stratification and graded sandstone beds. The sandstones are yellowish gray, and yellowish white and locally ~30 m (~100 ft) thick. The Dakota at this location is heavily vegetated.

The Dakota is uncomfortably overlaid by a Porphyritic Granodiorite (gp) associated with the Laramide orogeny during late Cretaceous-early Tertiary. It is uniform in composition and texture and is 12-30 m (40-100 ft) thick and thickens outside of the study area.

Much of stratigraphy is covered to the east of the study area by Pleistocene landslide deposits mixed with alluvium and glacial till. Several large gullies have formed along the steep slopes and cliffs cutting through the multiple lithologies. These gullies act to channelize runoff from storms and meltwater and are prime examples of the variability of the different rock type's resistivity.

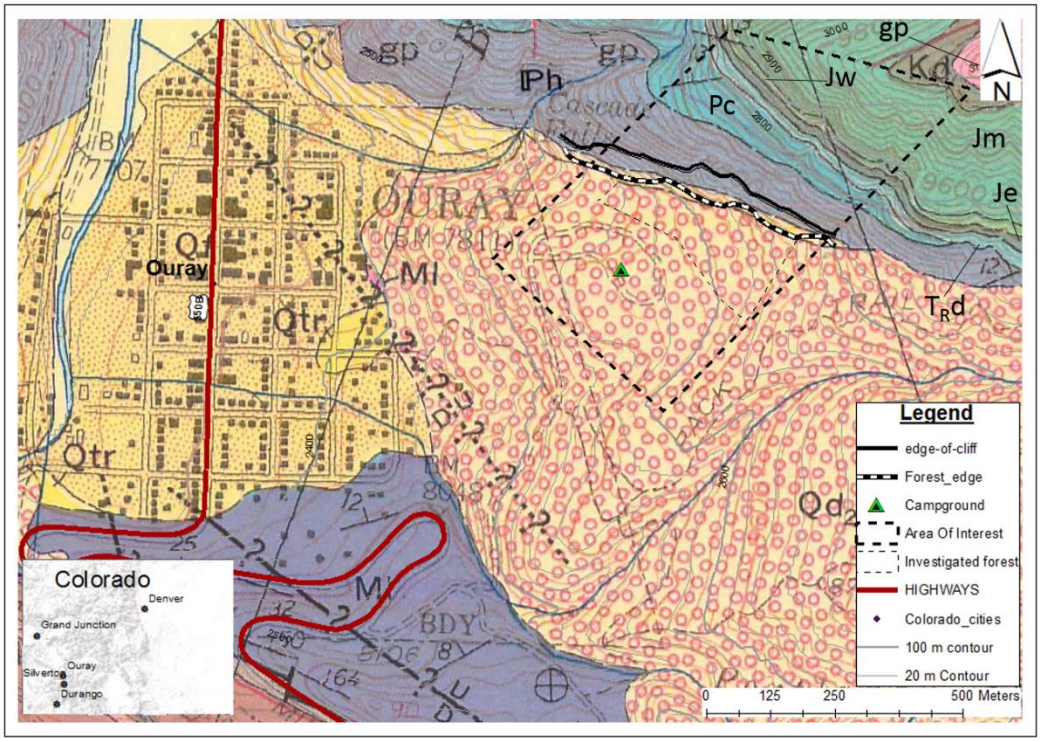

Figure 7 Geologic map of Ouray, Colorado and the study area (modified after Luedke and Burbank, 1962)

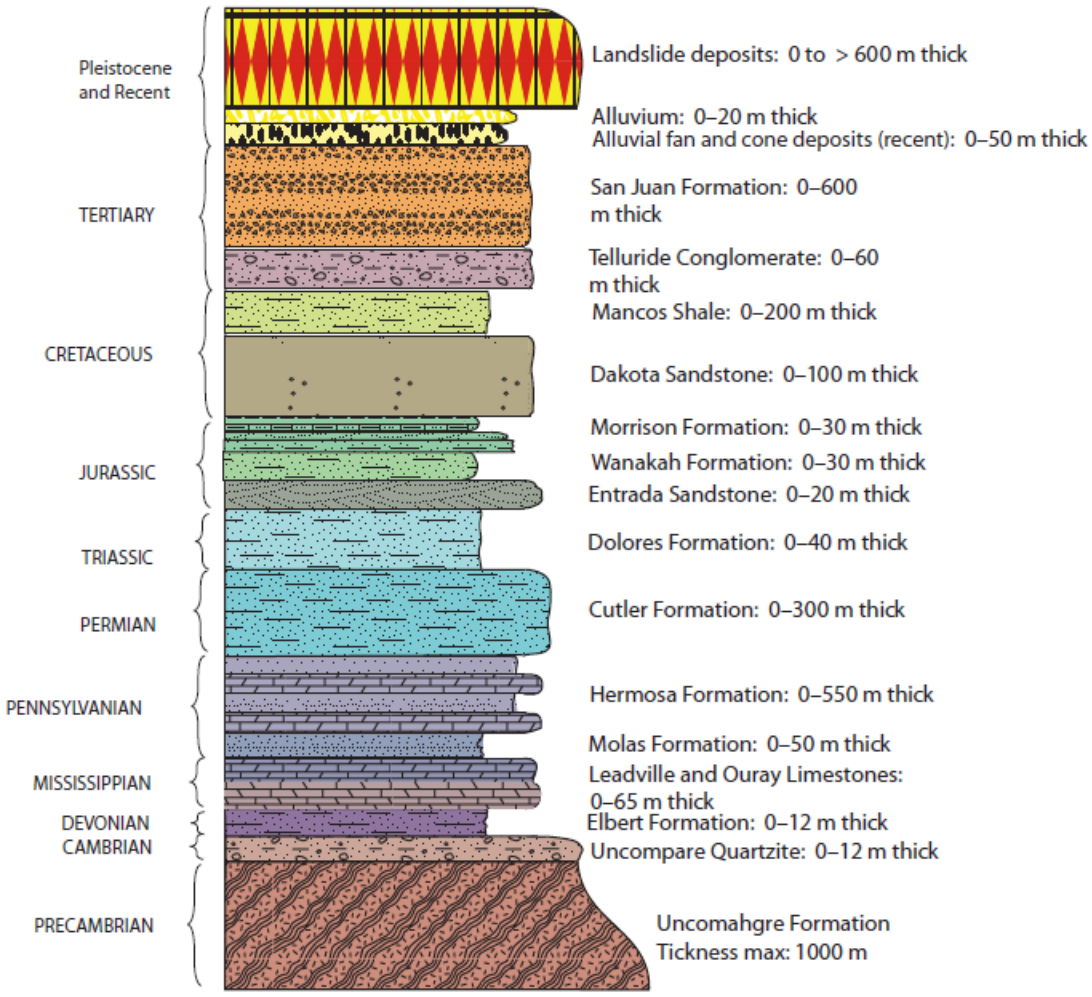

Figure 8 Stratigraphy of the Ouray, Colorado quadrangle (from Reed, 2013)

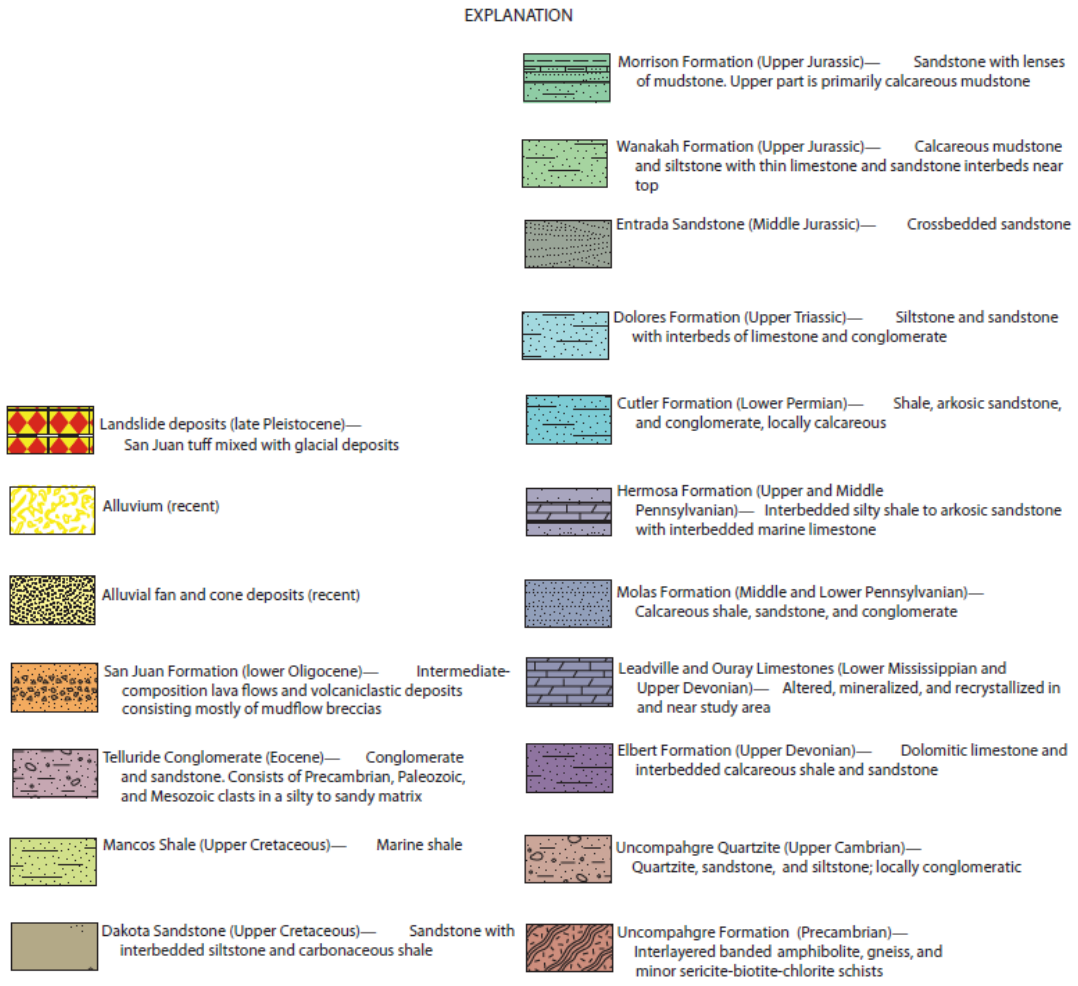

Figure 8 Continued

3.3 Climate

The climate of Ouray is humid continental and has four distinct seasons. Temperature and precipitation are slightly increased at higher elevations (Ouray, 2008). The annual average length of the day is 12.7 hours (NOAA, 2013). Table 2 provides monthly climate summaries for Ouray. Average annual max. temperature Cº (Fº) for Ouray is 13.7º (56.6º) and average annual min. temperature is 0º (32º). Total annual precipitation based on monthly averages is 23.1 m (75.8 ft) and total annual snowfall

based on monthly averages is 140.2 m (460 ft) (NOAA, 2013). Figures (9 and 10) show Ouray's daily temperature averages and extremes. The coldest months in Ouray are December, January, and February. The last freeze usually occurs late May to early June. The warmest months in Ouray are June, July, and August. Overall, daily temperature fluctuates ~25 º F.

Annual precipitation is ~ 100 cm (40 in) in the high mountainous regions near Ouray, however, is ~ 30-40% of precipitation is snowfall (WRCC, 2015; Ouray, 2008). Much of the rainfall occurs during the spring, summer, and early fall. The rainfall's duration and intensity is highly dependent on the "southwest monsoon" from mid-July to late August. Ouray, on average experiences more rainfall from the seasonal monsoon during La Nina years (WRCC, 2015; Ouray, 2013). More information regarding notable historic and recent floods can be found at the Storm Events Database -National Climatic Data Center (*http://www.ncdc.noaa.gov/stormevents/*).

Table 2 Monthly climate summaries for the two weather stations in Ouray, Colorodo from 06/01/1893 to 01/20/2015 (Source: Western Regional Climate Center, **wrcc@dri.edu**)

OURAY, COLORADO (056203) & (056205)

Period of Record Monthly Climate Summary

Period of Record : 06/01/1893 to 01/20/2015

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	35.95	38.2	45.85	53.55	63.1	75.15	79.15	76.85	70.6	59	46.45	36.4	56.65
Average Min. Temperature (F)	14.35	16.65	22.9	29.5	37.25	45.8	51.85	50.8	44.1	33.75	24.1	16.25	32.3
Average Total Precipitation (in.)	1.64	1.84	2.22	2.44	1.865	1	2.625	2.25	1.865	2.035	1.58	2.16	23.52
Average Total SnowFall (in.)	25.65	27.7	32.65	22.8	6.8	0.15	0	0	0.15	6.1	18.45	31.45	171.8
Average Snow Depth (in.)	9	11	7.5	2	0	0	0	0	0	0	2	6	3

Source: Western Regional Climate Center, wrcc@dri.edu

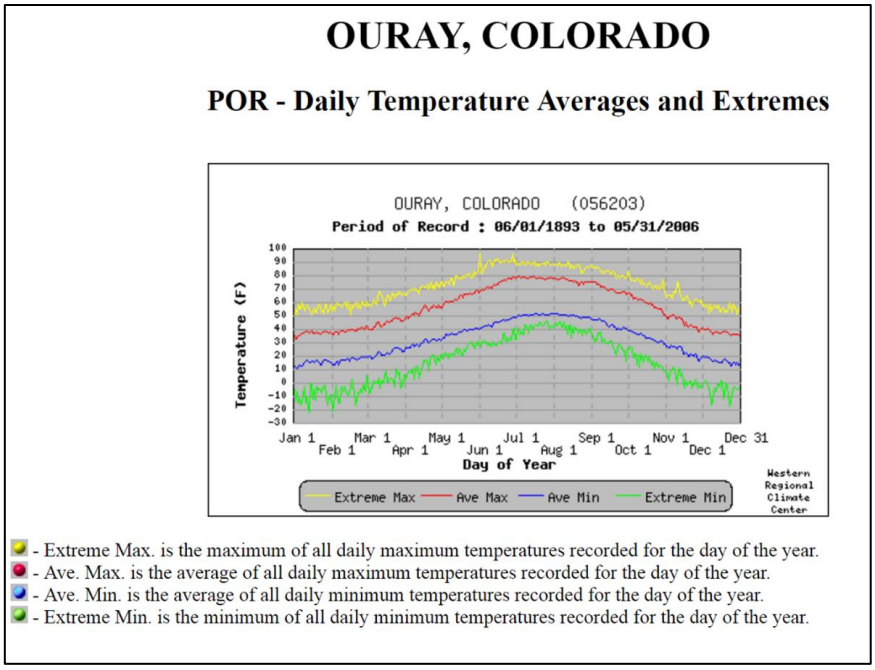

Figure 9 Daily temperature averages and extremes for weather station (056203) from 06/01/1893-05/31/2006 (WRCC, 2013).

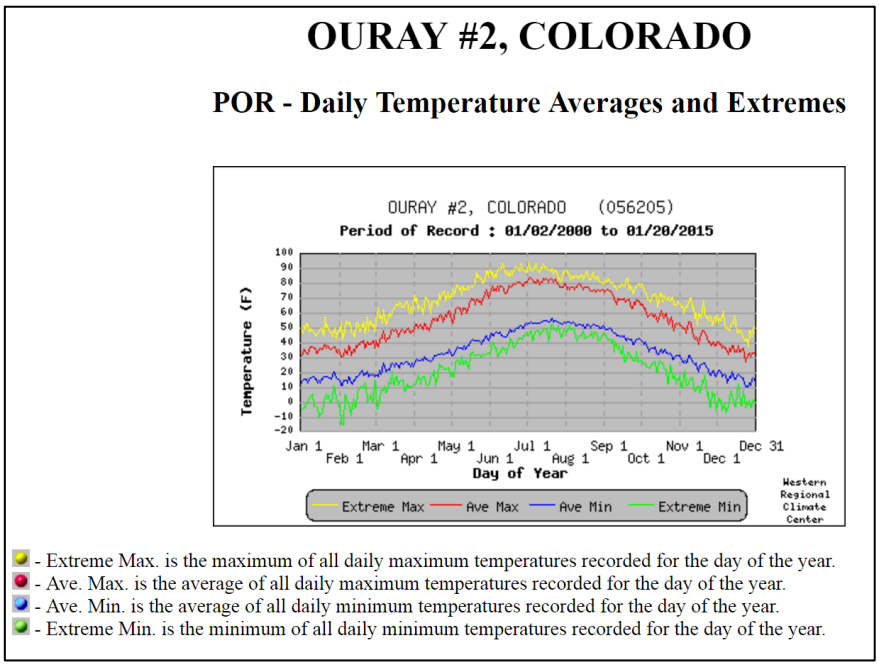

Figure 10 Daily temperature averages and extremes for weather station (056205) from 01/02/2000-01/20/2015 (WRCC, 2013).

Figures 11 and 12 show snowfall and snowdepth averages and extremes for Ouray from 1893 to 2016. Winter storms can produce high winds, extreme temperatures, and deposit large volumes of snow in a short period of time. Large winter storm events can detach boulders from cliffs or initiate moment of unconsolidated rock fragments on steep slopes. Notable winter weather events can be found at (SHELDUS, 2013; Ouray, 2008). Notable wind storms, excluding winter storm events, usually occur between the months of April and September (SHELDUS, 2013; Ouray, 2008).

Colorado has experienced periods of significant drought in 1890-1894, 1898-2004, 1930-1940, 1950-1956, 1974-1978, 1980-1981, 1989-1990, 1994-1997, 2000-2006, and 2010-2013 (State of Colorado Drought Mitigation and Response Plan, 2013; Drought and Water Supply Assessment, 2004). Droughts can inhibit tree growth and destabilize root structures (Shroder, 1978). Colorado experienced notably dry winters during 1976-1977 and 1980-1981 (Drought and Water Supply Assessment, 2004). Ouray County experienced multi-year droughts from 2000-2006 and 2010-2013 (Fuchs and Bathke, 2016). Notable recent droughts occurred during the summer of 2002, and from 2010-2013 (State of Colorado Drought Mitigation and Response Plan, 2013; Fuchs and Bathke, 2016).

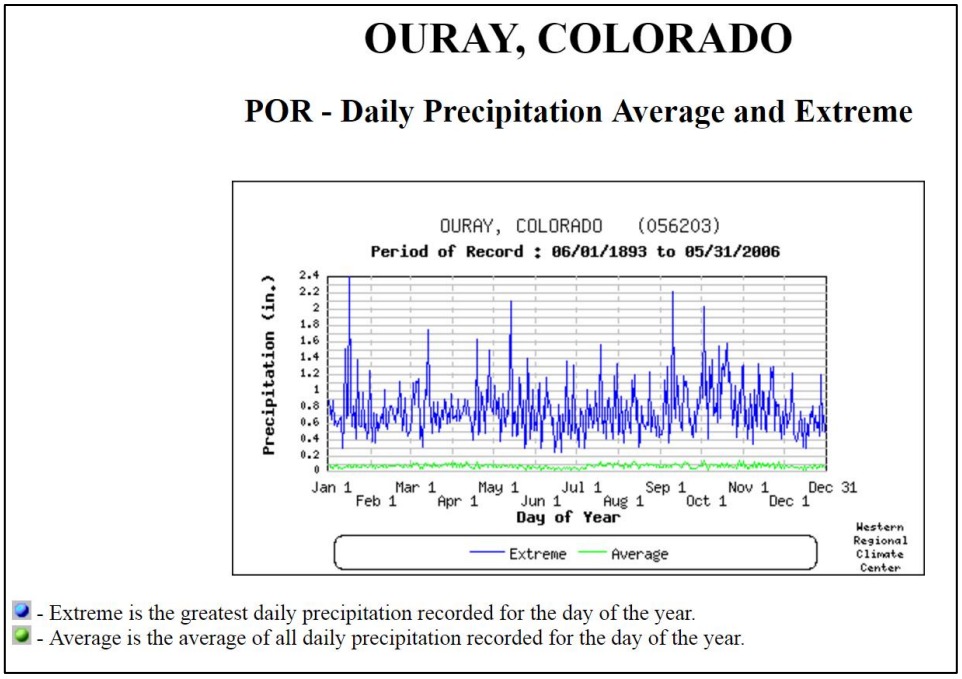

Figure 11 Daily precipitation averages and extremes for weather station (056203) from 06/01/1893-05/31/2006 (WRCC, 2013).

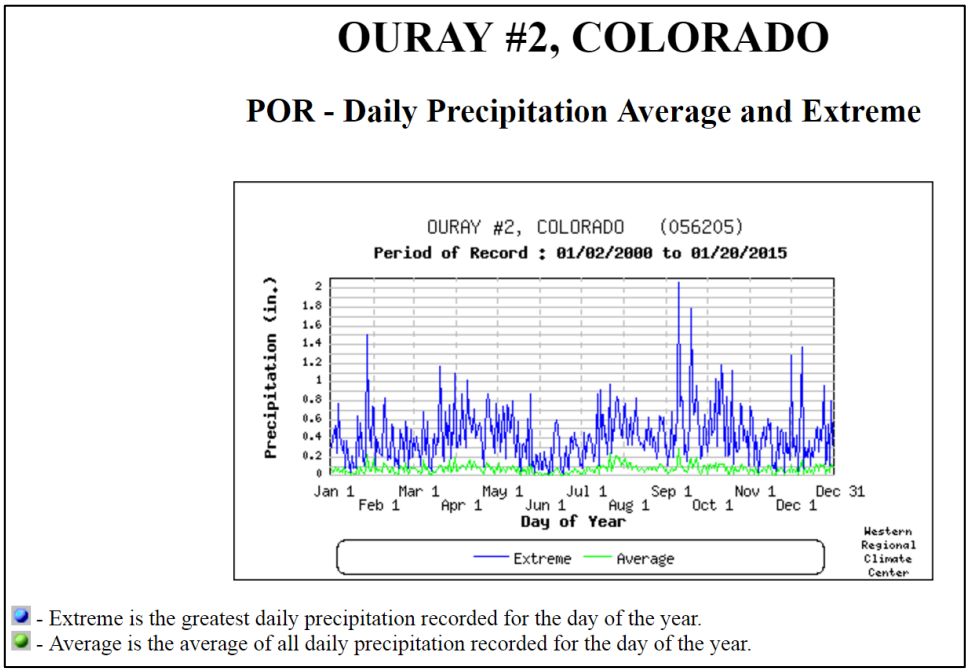

Figure 12 Daily precipitation averages and extremes for weather station (056205) from 01/02/2000-01/20/2015 (WRCC, 2013).

3.4 Vegetation

The investigated forest stand is approximately 43,500 m^2 (468,230 ft^2) and has moderate to high vegetation cover. The forest is predominately *Abies concolor* (White fir), *Pseudotsuga menziesii* (Douglas fir), *Picea pungens* (Blue spruce), a few *Pinus ponderosa* (Ponderosa pine), *Picea engelmannii* (Engelmann spruce), *Abies lasiocarpa* (Subalpine fir), and dwarf stands of *Quercus gambelii* (Gambel oak or Oak brush).

The forest floor is relatively clear and easy to navigate through, consisting primarily of fallen fir and downed logs and snags of White fir (*Abies concolor*). Navigation became extremely difficult through areas with dense stands of Gambel oak or Oak brush (*Quercus gambelii*), typical of the proximal talas slope and areas with limited canopy coverage. This advantageous growth likely a result of the removal of larger vegetation from mass-movement events or beetle infestations.

3.4.1 Lichen

The five dominant species of lichen in Ouray are *Lecidea atrobrunnea* (brown crustose), *Lecanora thomsonii* (pale green foliose), *Parmelia spp*. (plae green fruticose), *Xanthoria elegans* (orange foliose), and *Rhizocarpon geographicum* (green crustose) (Hale, 1967; Carrara and Andrews, 1973).

3.5 Temporal Record of Activity

Two reports compiled for the city of Ouray (2008, 2013) and Jochim (1986) document notable debris flow events in the vicinity of Ouray, Colorado, that occurred in 1878, 1909, 1927, 1929, 1951, 1965, 1971, 1973, 1981, 1982, 1988, 2002, 2003, 2005, 2008, 2010, and 2013. The events of 1929, 1981 and 1982 were particularly wide spread

and devastating. The Colorado Geological Survey's (CGS) 2002 Landslide Mitigation Plan Update p. 3-190 listed the City of Ouray as a "Tier one debris flow area" and "needing immediate or ongoing action or attention because of the severity of potential impacts".

Active faulting in the region creates the potential for earthquake induced rockfalls. Notable earthquakes with epicenters in Ouray County or the neighboring San Miguel and Hinsdale Counties include 1894, 1897, 1913, 1955, 1960, 1962, 1967, 1970, 1989, 1994, 2006, and 2013. (Colorado Earthquake Evaluation Report, 2007; Colorado Geological Survey, 2015; Ouray, 2008, 2013) The strongest earthquakes occurred during 1913 and 1960 with reports of rocks rolling down the steep slopes and cliffs surrounding Ouray (Ouray, 2013).

The Ouray County Multi-Hazard Mitigation Plan (Ouray, 2013) lists areas at risk for landslides and rockfalls. Records of rockfall activity usually occur along roadways, specifically highway 550, as the increase traffic will record more events. Other areas, such as the study site considered for this assessment will require an alternative approach to create a record of rockfall activity.

CHAPTER IV

METHODS

Chapter IV presents the methodology used in this thesis and recaps specific techniques used in the field and in the lab. The reader is provided criteria for site selection, procedures for core extraction and associated tree-ring analysis, and descriptions of the dendrogeomorphic approaches considered for this assessment (figure 13).

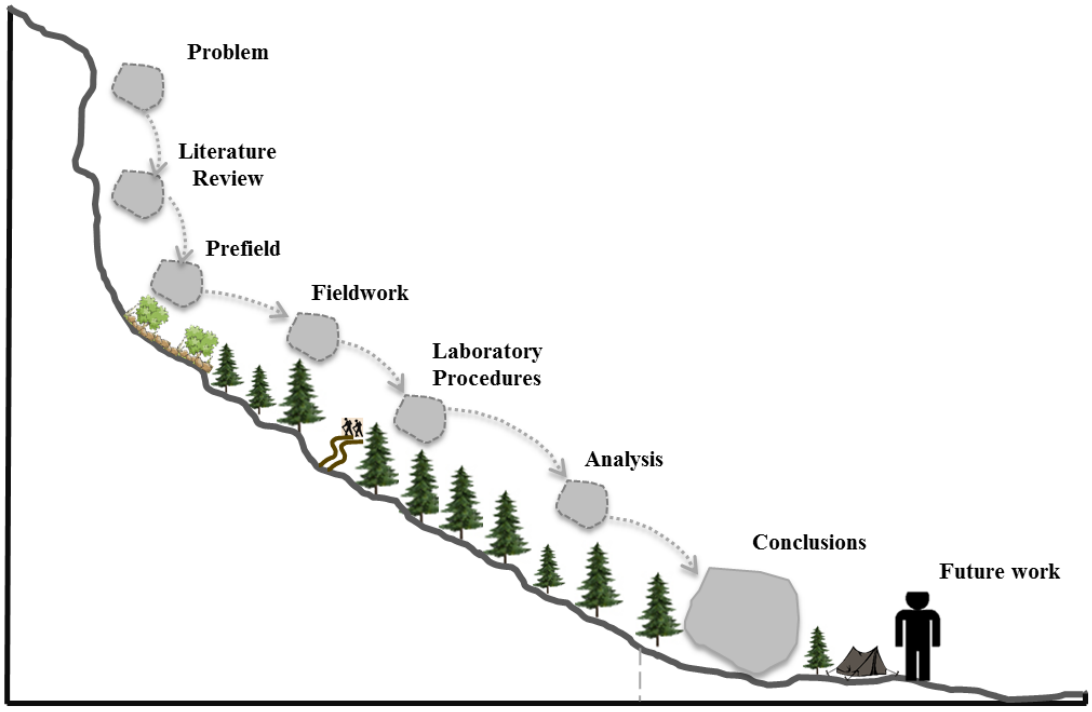

Figure 13 Diagram illustrating the methodology process

4.1 Dendrogeomorphology

The term 'dendrogeomorphology' was coined by Alestalo (1971) and stands for the analysis of growth reactions of trees affected by geomorphological processes by

dendrochronological methods (Alestalo, 1971). Annual tree-ring growth is initiated in the cambium as phloem and xylem cells differentiate. The internal heterogeneity of the tree rings are a result of the variations in the cell sizes and cell-wall thickness. The initial spring-time growth termed ‘earlywood”, is characteristic of large thin-skin cells. Earlywood growth is followed by ‘latewood’ growth nearing the end of the growing season with cells tending to flatter and thick-skinned cell walls (Shroder, 1978). Annual ring growth can be altered where the sequence is missing a ring or contains a false ring if normal growing conditions are interrupted (Schweingrober, 1996).

4.1.1 Identifying Tree Types

Trees are either coniferous or deciduous, and exhibit unique growth rituals. Deciduous trees produce new leaves every spring after dropping them in fall, and remain leafless in winter. Deciduous trees grow in nutritious soil in temperate climates and have broadleaves, where the thin large surface can collect large amounts of sunlight for photosynthesis. Deciduous trees are commonly referred to as “hardwood”. Coniferous trees produce seed-bearing cones and are typically needle leaved evergreens (Strunk, 1997). Conifers grow in areas with nutrient poor soils and extreme environments. The needles are small and durable as they retain their needles for photosynthesis year round. The steep slopes and shallow soils of landslide materials on the Ouray, Colorado Amphitheater are typical for coniferous trees. The conifer species observed in this study are pine, fir and spruce trees. Tree species are differentiated using standard botanical techniques (Petrides and Petrides, 1992).

Abies concolor (White fir) wood is light, soft, weak, deteriorates shortly after death and is usually not sought out for its lumber. It has wide annual tree rings and lighter colored sapwood. *Abies concolor* typically has a slow growth rate and medium tolerance to drought and restricted water conditions. The annual radial growth of *Abies concolor* is highly responsive to annual climate fluctuations (Hurteau et al., 2007). The strong influence of climate on annual tree-ring growth can create difficulties isolating changes of increment rates as a result of changes to microsite conditions (i.e. geomorphic processes) or from climate effects (Tardif et al., 2003; Hurteau et al., 2007).

4.1.2 Dendrogeomorphic Evidence of Disturbed Trees

Shroder (1978, 1980) presented the "process-event-response" model to expand upon the interrelationship of key characters of dendrogeomorphology. The "process" is the rockfall or other geomorphic agent. An individual geomorphic "event" that affects the tree may result in a unique growth "response". Figure 14 illustrates the visual evidence of disturbed trees as a response to rock-fall activity including: (a) Decapitation, (b) visible injury or scaring from impact, (c) tilting, or (d) elimination of neighboring trees or 'broken crown' (Schweingruber, 1988; Stoffel et al, 2005a; Stoffel et al, 2005b; Stoffel, 2006; Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014).

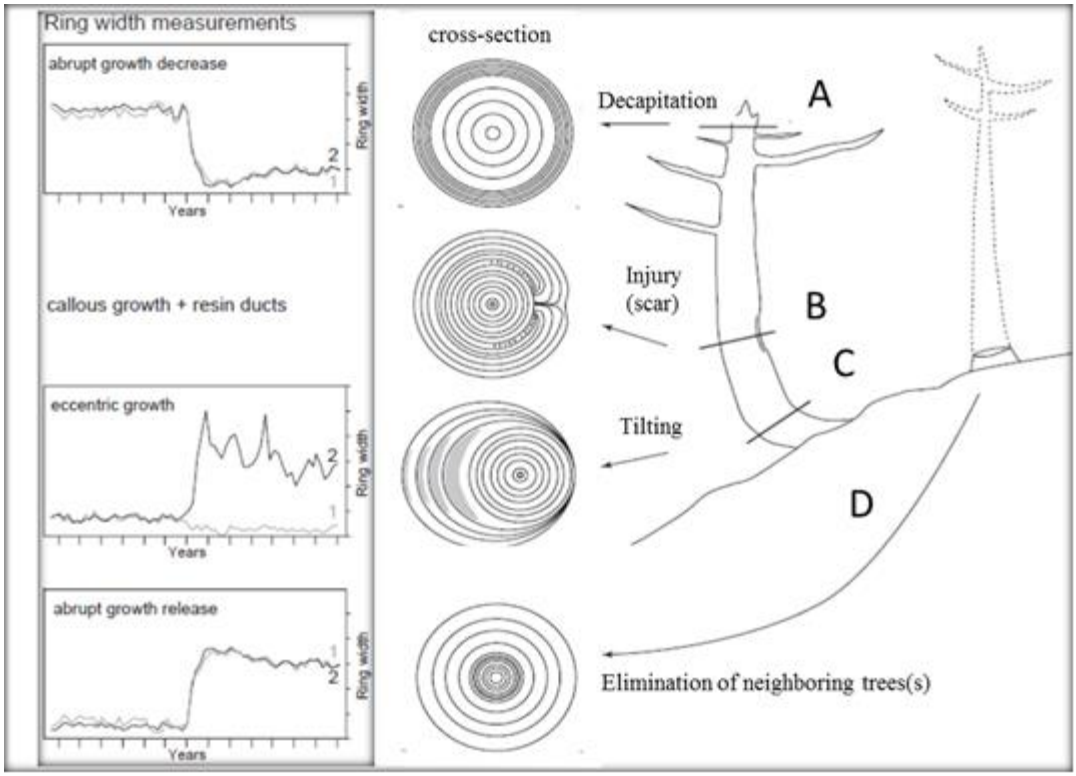

Figure 14 Dendrogeomorphic evidence to infer rockfalls. Variations of tree-ring width measurements (left) and the visual result of disturbed samples (Modified from Stoffel et al., 2005)

4.1.2.1 Decapitation

The decapitation of a tree or the removal of its branches as a result of falling or bouncing rocks and boulders will result in an abrupt decrease of annual ring growth or suppression. Suppression is growth retardation in which stressed trees produce less wood and the annual increment is smaller whereas tension is the opposite. When new sprouting branches form apical dominance that replaces the broken stem or crown, it is referred to as "candelabra" growth (Stoffel et al., 2005c).

4.1.2.2 Injuries or Wounds (Scars)

When falling rocks or debris impact a tree with enough force, a mechanical wound (injury or scar) will respond with the growth of callus tissue or tangential rows of traumatic resin ducts (TRDs) (Stoffel et al., 2010; Schneuwly et al., 2009). Injuries or wounds can occur on a tree's trunk, branches or roots (Stoffel et al., 2010). Impacts can cause local destruction of the cambium, to which the tree will respond by halting new cell formation in the injured area, and will start producing chaotic callus tissue on the edges in an attempt to overgrow the wound with cambium cells from the edges (Larson, 1994; Schweingruber, 2001, Stoffel et al., 2010). The nature of the wounds healing is dependent on several factors and will be discussed in greater detail in a later section.

Impacts to select conifer species will produce tangential rows of traumatic resin ducts (TRD) in the developing xylem. *Abies concolor* (White fir) does not produce TRD's. Erosion or other geomorphic processes can partially expose roots. Root damage or injury can cause periods of suppression of tree-ring growth (Rizzo and Harrington, 1988; Stoffel et al, 2010).

4.1.2.3 Tilting (Inclination) of Stems

The sudden or gradual introduction of stress or pressure applied to a tree by a geomorphic agent or by the destabilization of a trees foundation will result in the inclination, or tilting or bending of trees (Schweingruber, 1996; Bollschweiler, 2007). Growth responses attributed to inclination include eccentric ring growth and; for deciduous trees, the pith is displaced on the downslope side and reaction wood (tension) balancing it on the opposite side; for coniferous trees, the displaced pith is upslope

coupled with (suppression) and balanced on the downslope side by reaction wood (Braam *et al*., 1978a). Normal (complacent) ring growth consists of concentric ring development at equal rates, whereas (sensitive) ring development occur within stressed trees (Winchester et al., 2007). Normal ring growth must be evaluated considering all influencing factors as suggested by (Schweingruber, 1990): "exposure, temperature, precipitation, wing, light, growing period length; competition and soil (type, texture, water, nutrient and oxygen availability)." Additional growth responses can be related to geomorphic processes.

Another growth response is the disruption of original apical dominance and formation of new sprouts which commonly grow vertically upward from the tilted trunk (Schroder, 1980). Note reaction-wood growth is the gravity controlled response of a tilted tree to strengthen its lower trunk when supporting the returned vertical alignment of the upper trunk (Schroder, 1980). The adverse tree ring growth response of tree tilt and position with respect to the slope is fundamental in differentiating annual ring width variations.

In the event of a sudden geomorphic event, such as a debris flow, landslide, rockslide, or other movement deposited material may bury the base of a trunk of a tree. The disruption of the water and nutrient supply will cause temporary annual increment growth suppression (Strunk, 1997).

4.1.2.4 Elimination of Neighboring Trees and Colonization

Geomorphic processes, such as rockfalls, debris flows or avalanches can eliminate trees in its pathway while leaving surrounding trees standing. The lack of

competition creates favorable growing conditions which are observed in core as growth release or larger increment rings (Schweingruber, 1996; Stoffel et al., 2005a.c). In the case of elimination of large portions of the forest stand, germination ages of new trees colonizing the bare landform can be used to establish a minimum date of disturbance (Schneuwly, 2009; Stoffel et al., 2010).

4.2 Field Methods

To delineate areas of rock-fall activity, a detailed geomorphic investigation will include remote sensing and on site field analysis. Satellite and aerial photography along with topographic, geologic and vegetation surveys were used to determine the geographical extents of the study area of interest.

A global positioning system (GPS) and aforementioned maps were used in the field to map areas of talus accumulation. The block shape, lithology, and diameter of selected cobbles and boulders were recorded and a note was made of their general relationship to surrounding clasts. In addition, this study followed standard lichenometry procedures (Hale, 1967; Carrara and Andrews, 1973; Luckman and Fiske, 1995; Bull and Brandon, 1998; Bull, 2004). Procedures include recording the general presence of lichen growth, the dominant species, and measuring the five largest lichen diameters for further analysis.

GPS was also used to record the locations of trees exhibiting visual evidence of rock-fall activity (figure 15). The type and number of visible defects were then recorded. By identifying trees impacted by rock falls, I can map the spatial extent of rock-fall

activity. Selected trees may be sampled for further dendrochronological applications. The spatial distribution of trees sampled is given in figure 16.

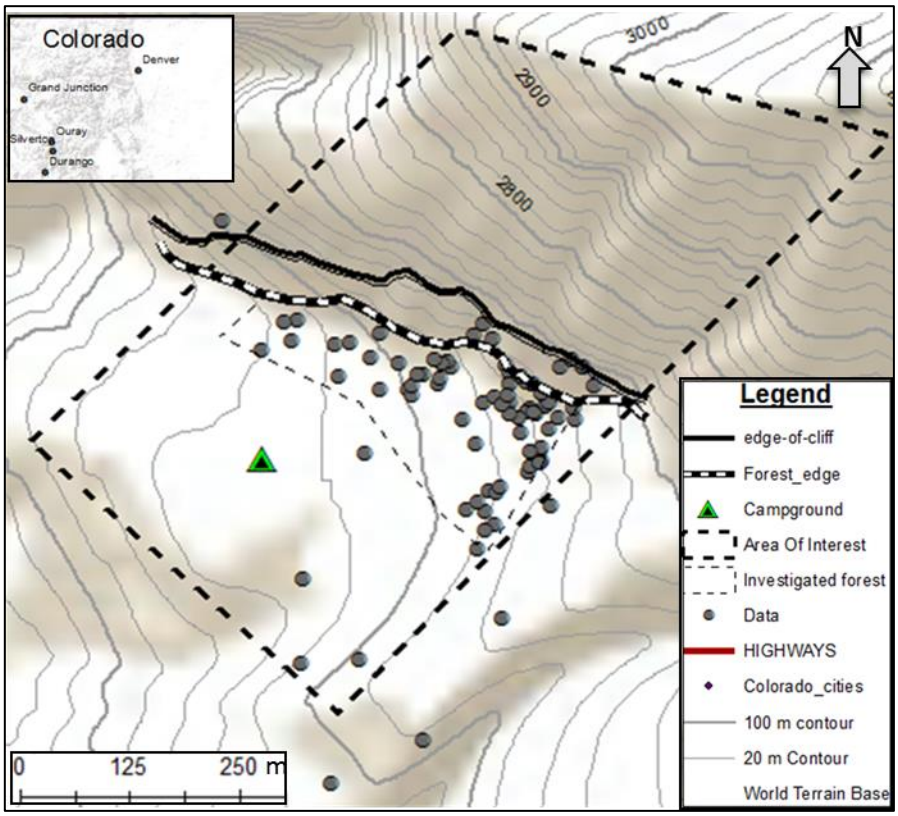

Figure 15 Visualized locations of data samples.

Figure 16 Imagery displaying the location of sampled trees. Yellow circles represent sampling locations.

Establishing a temporal chronology requires a view of past activity. This perspective can be obtained through the use of tree rings of trees impacted by rock falls. Selected trees were sampled by carefully extracting tree cores ~5 mm in diameter using an "increment borer" (figure 17). The cores are visually and statistically analyzed later in the lab to assess tree-ring growth responses to rock-fall activity and construct a rock fall chronology.

Figure 17 Core extracted from an injured tree using an 'increment borer' (Photo by Author)

This study employed a dendrogeomorphic approach (Fitts, 1976, 1971; Grissino-Mayer, 2001, 2003; Stokes and Smiley, 1968; and Speer, 2010; Shroder, 1978, 1980), tailored for rock-fall analysis (Stoffel et al., 2005; Stoffel &Bollschweiler, 2008; Stoffel, 2006). Existing literature primarily focuses on modeling the physical response of rock-fall events, whereas this study will investigate the cause-effect response and the dynamic variables associated with rock-fall hazard assessment.

Stoffel et al. (2005), Grissino-Mayer (2003), and Speer (2010) outline procedures for individual core extraction based on targeting trees with visible defect. Cores typically are taken from the up and down-slope sides (figure 18, A & D). When visible injuries or growth defects are present, additional cores may be taken perpendicular to slope and within or near wounds and into the overgrowth callus tissue (figure 18, C & B) (Stoffel & Bollschweiler, 2008; Stoffel et al. 2005; Stoffel, 2006; Trappmann and Stoffel, 2013).

After a core has been extracted from a tree, it is placed in a (plastic or paper) straw for protection during transportation. All tree cores are labeled according to site specifications and a site identification card is completed for each location (Shroder, 1980).

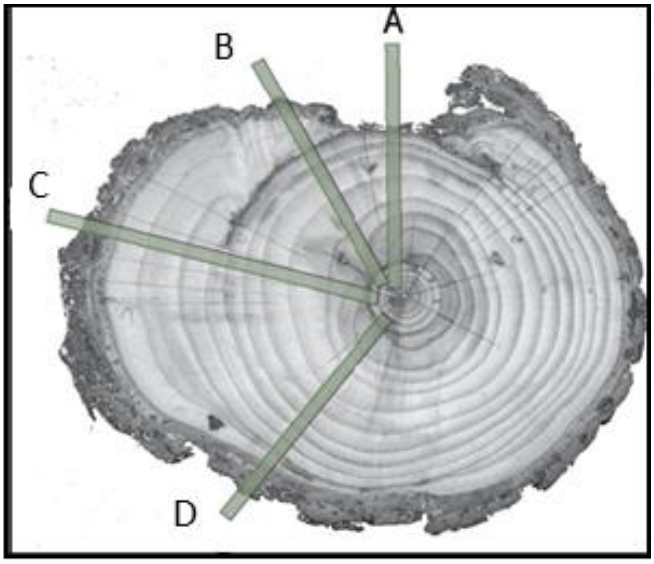

Figure 18 Cross-section of scarred tree with ideal sampling positions A-D (Modified from Stoffel and Bollschweiler, 2008)

4.3 Lab Methods

To construct a rock-fall chronology, the tree cores annual growth rings were dated and measured. Prior to analysis, the samples were prepared for further analysis. All core samples were dried and glued to wooden core mounts to be sanded using progressively finer sand paper (40 to 400 grit), to reveal the cellular structure of the tree rings. Annual ring growth can be altered where the sequence is missing a ring or contains a false ring if normal growing conditions are interrupted (Schweingrober,

1988). To rectify this, the cores were cross-dated using skeleton plots (Stokes and Smiley, 1968; Speer, 2010) and or the listing technique (Yamaguchi, 1991). This approach was used to visually indicate drastic changes of climate or geomorphic events, because they are recorded in the trees growth patterns (Winchester et al., 2007). Precise measurement of annual tree-ring widths (or the latewood-earlywood transitions) was accomplished using a binocular stereomicroscope and a sliding-stage micrometer interfaced with the recording software "Measure J2X" (Robinson and Evans, 1980; Speer, 2010). The accuracy of the cross dating was be verified statistically using the software COFECHA (Grissino-Mayer, 2001; Holmes, 1983; Speer, 2010) (APPENDIX E).

In consideration of ring-width variations resulting from climate change, many dendrochronologist apply a corrective procedure called standardization (Fritts, 1971, 1976). Standardization corrects for the decrease of annual ring width as the tree ages and grows wider. Standardization will correct for the ring growth variation of the youngest rings to a normalized ring width variations, as the variation in ring width for the younger growing rings will be drastic because of the fast rate of growth. Additional fluctuations to tree growth can be related to abrupt GD caused by falling rocks. Figure 14 shows variations of tree-ring width measurements as a trees response to rock-fall induced GD. Analysis of the initiation, duration, and termination of these growth defects (GD) are used to establish a rock-fall chronology.

Recurrence intervals of rockfalls within the forest stand were then calculated by dividing the age of a tree at DBH by the total number of dated GD for the tree (Stoffel et

al., 2005b). This step allowed for the visualization of absolute values of rockfall frequency at the tree level.

Rockfalls typically consist of single falling, bouncing or rolling rocks which may only impact trees along their limited trajectories and constrained by the size of the clast (Dorren et al., 2007; Schneuwly and Stoffel, 2008a; Stoffel et al., 2011). The recurrence interval of rockfalls may, however, overestimate the more recent injuries and underestimate the older events clouding the historical distribution of areas with preferred rockfall trajectories. This is because as trees grow, their thick stem makes them a larger target for rockfall impacts than smaller trees and thus are more likely to record GD. To compensate for this, we used a yearly rockfall "rate" (Stoffel et al, 2005b), expressed as the number of rockfall events per meter width of all tree surfaces present per year:

(1)

$$RR_n = \sum \frac{GD_n}{\sum ED_n}$$

where GD_n stands for the number of reconstructed GD (or injuries) in year n, and ED_n represents the sum of all DBH (in meters) values of the sampled trees (i.e. exposed diameter, ED) existing at the beginning of year n. To calculate ED values, yearly DBH increment of each tree and each year were determined by dividing the DBH at sample year by the tree age. The rockfall "rate" was then obtained by dividing the yearly sum of reconstructed GD by the ED. Rockfall rate is expressed as rockfall events m^{-1} yr^{-1} assuming constant increment rate and disregarding juvenile and aging trends (Stoffel et al., 2005b; Stoffel et al., 2011).

To add to the rockfall chronology, a third approach, adapted from (Trappmann and Stoffel, 2013; Trappmann et al., 2013) classifies impact wounds or injuries of *Abies concolor* (White fir) into age categories by visual inspection of wound recovery and closure. A reference data set was created, listing actual impact ages from core samples matched with relative visual examples of the wounds recovery stage. For each tree exhibiting an injury or scar, the tree size, the scar size, and notes regarding the position and condition of neighboring trees were considered.

Digital data are visualized using Arcgis 10.3® and GoogleEarth® (ESRI, 2015; Google, 2015). Colorado county and state data were downloaded as shapefiles from the US Census Bureau website (*http://www.census.gov/geo/maps-data/*). A Digital Elevation Model (DEM) with 10 m resolution was downloaded (Coughenour et al., 2015). The DEM was then clipped to only encompass the city and the slopes surrounding the Amphitheater (DEM1). Spatial visualization of the tree-ring data were investigated using the ESRI ArcGIS 10.3 software (ESRI, 2015). Tree locations were converted to geo-objects and included the following data attributes: "tree coordinates, tree age; number, year and type of GD, DBH, injury heights, injury age classification, as well as information on ground vegetation and crown condition, clast size and lithology, and lichenometry measurements and species type". Return periods (recurrence intervals) were visualized using ArcGIS 10.3 Geostatistical Analyst software extension (ESRI, 2015) to examine the special relationship between data points. Surfaces were interpolated with an Ordinary Kriging model, using five neighboring trees.

CHAPTER V

ANALYSIS

This chapter presents the results of the tree-ring assessment and initial analysis of the spatial extent of rockfalls and a minimum rockfall time-series. The finding presented will answer the questions: (i) where spatially is the slope subjected to rockfall activity and what are the magnitude and frequency of events? Also, (ii) will reconstructing a rockfall chronology using a dendrogeomorphic methodology of *Abies concolor* (White fir) help identify potential triggering mechanisms?

5.1 Tree Rings-Master Chronology

A master chronology was created using increment cores from 32 trees, so that samples could be cross dated accurately. Results from COFECHA show an interserries correlation to the master is .669 with an average mean sensitivity of .374.The master series dates span from 1800 to 2015 (APPENDIX E)

5.2 Rockfall History

This analysis used 28 of the 60 samples collected from the study site were used to generate a preliminary rockfall chronology, and 20 of the 28 dated samples were used for rockfall analysis. Unfortunately, 2 samples were destroyed in transit from the study site, and 2 were undateable due to abnormal growth defects.

5.3 Visible Defects and Growth Responses to Rockfall Activity

Field investigation identified 152 visible defects on 64 *Abiesconcolor* (White fir), 6 *Pseudotsugamenziesii* (Douglas fir), and 1 *Quercusgambelii* (Gambel oak or Oak brush) (Table 3). As illustrated in Table 4, recent to overgrown injuries (scars) was

predominate visible defect identified in 97 cases (63.8%), followed by 20 cases of 'broken crown' (13.2%), 19 trees with tilted stems (12.5%), and 16 cases of decapitated trees (10.5%).

Table 3 Number of trees and injuries sampled

	Abies concolor (White fir)	*Pseudotsuga menziesii* (Douglas fir)	*Quercus gambelii* (Gambel oak or Oak brush)	*Total*
Number or trees	64	6	1	71
Number of visible injuries	135	14	3	152

Table 4 Overview of visible defects used to determine rockfall events

		%
Injuries (scars)	97	63.8%
Broken crown	20	13.2%
Tilted stem	19	12.5%
Decapitation	16	10.5%
Total	152	100.0%

The analysis of 28 cores revealed a total of 121 GD as result of rockfall activity (Table 5). GD identified in multiple cores of the same tree, caused by the same impact were omitted from these results. Injuries and callus tissue were the predominate GDs, observed in 37(30.6%) and 29(24.0%) cases respectively. Abrupt growth suppression occurred in 25 cases (20.7%), and growth release occurred in 26 cases (21.5%). Reaction wood could only be found in 3 samples (2.5%). Traumatic resin ducts (TRD) was only identified in 1 sample (0.8%).

Table 5 Overview of growth disturbances used to determine rockfall events

Growth disturbances	Number	%
Injuries	37	30.6%
Callus tissue	29	24.0%
Growth suppression	25	20.7%
Growth release	26	21.5%
Reaction wood	3	2.5%
Traumatic resin ducts (TRD)	1	0.8%
All reconstructed events	121	100

5.4 Spatial Distribution of Growth Disturbances

The spatial distribution of reconstructed rock-fall activity varied considerably along the investigated forest stand. Analysis of rockfall recurrence intervals reveals rockfall activity is highest in the north-northwestern section of the study area, which is closest to the source of rockfalls. The record of rockfall disturbances decreases away from the forest edge because of the protective nature of the forest as neighboring trees above act as a shield to falling, bouncing and rolling rocks. The recurrence intervals at the stem level are listed in APPENDIX C, and the spatial distribution of interpolated recurrence intervals are illustrated in Figure 19. Both datasets point to the fact that areas with preferred rockfall trajectories generally record higher return periods of rockfalls (decadal scale), whereas lower return periods of rockfalls are recorded on sampled trees protected by neighboring trees or located in a topographically favorable area.

Based on visual inspection of the extent of healing of injuries or corrasion, consistent with results from core samples, scarred trees were placed into scar age classifications based on sages of recovery. As mentioned previously, the extent of the

wounds healing is highly dependent of the annual increment rate, tree age, and scar size (Stoffel et al., 2010), so to minimize error, three age categories were established to satisfy these conditions.

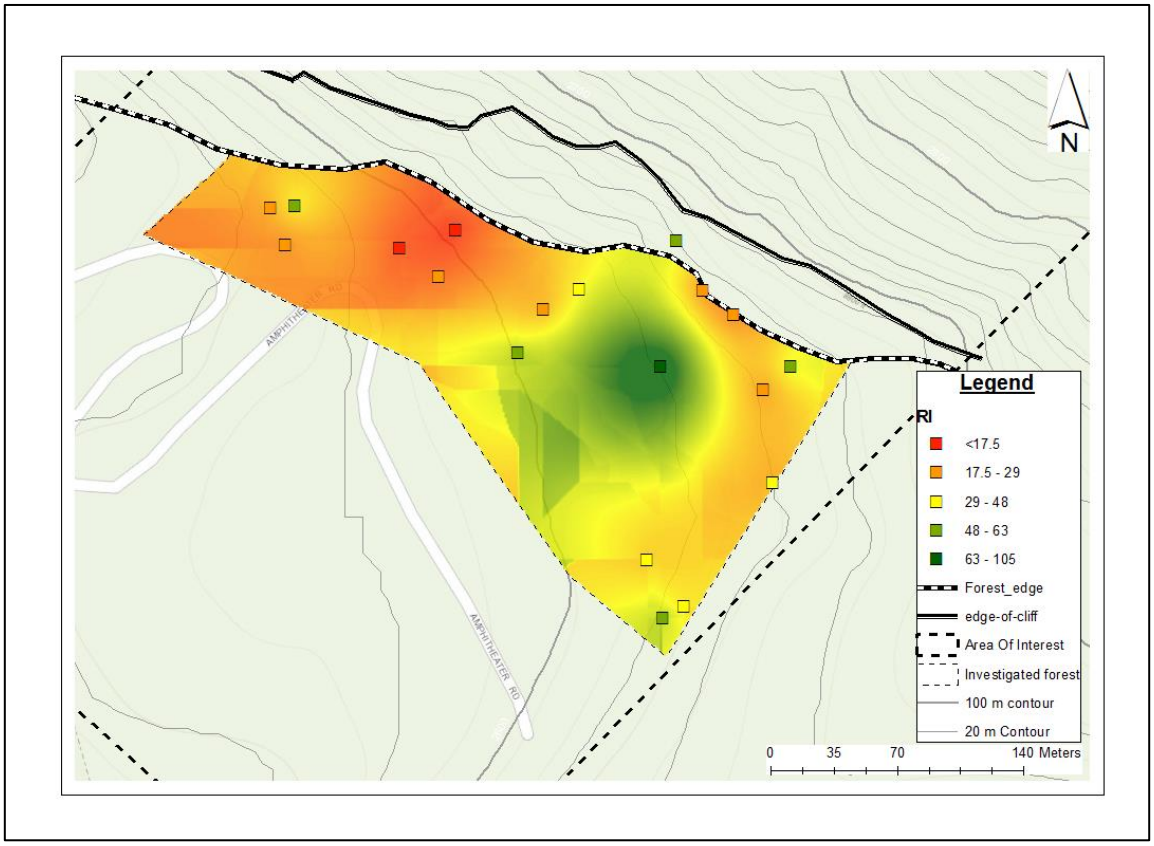

Figure 19 Reconstructed rockfall return intervals.

For this thesis, I used *Abies concolor* (White fir) trees, of which there is little to no existing literature when used for dendro methods. I created a reference data set from tree cores to establish an estimated rate of recovery, and then placed trees based on visual examination of wounds recovery stage into one of three categories. Analysis

shows that for an 105 year old *Abiesconcolor* (White fir) tree with a 24 cm (9.44 in) in diameter scar, an average of 66 years are needed for complete overgrowth and closure of the scar. As suggested by Trappmann and Stoffel, (2013) and Trappmann et al., (2013) relative dating based on visual inspection of wound closure and recovery presents considerable error, however, it is a viable means of relative dating to be used as a quality control (QC).

Abies concolor (White fir) trees exhibiting fresh injuries or corrasion with little to no recovery growth on healthy trees were considered to have occurred within the last 15 years and placed into 'Age Category 1'. Wounds of early to late stage of recovery exhibiting partial closure from callus tissue overgrowth were placed into 'Age Category 2' for impacts occurring before 2000 but after 1950. Completely overgrown injuries or scars in the late stages of recovery are placed in "Age Category 3' representing old rockfall events occurring before 1950.

Table 6 Injured trees categorized by relative recovery state

Age Category	Number	%
1 (2000-2015)	15	27.3%
2 (1950-2000)	20	36.4%
3 (<1950)	20	36.4%
All visible injuries	55	100

Table 6 shows the number of trees scared within each category. Figures 20, 21, & 22 visualizes the spatial extent of trees for the three-age categories. Here you can see the closed circles representing the location of the samples for each category. From this I was able to delineate areas with favorable rockfall trajectories through time.

Injuries of trees in groups 1 and 2 are primarily concentrated near the interface of the encroaching forest and talas slope which is between 30 and 60 m (100 and 200 ft). Injuries to trees in age-group 3 are more spatially diverse than trees in groups 1 and 2. Without knowing the nature of the investigated forest stands condition, difficulties arise when attempting to constrain forest stand presence past 1910.

The analysis shows that the areas to the upper left of the investigated forest are less active as compares to the areas of the upper right. Also, because we can see many of the same samples with recurring injuries through time this tells us that rockfalls have been continuous for the time of investigation and no large-scale mass-movement event occurred as the present trees would have been destroyed.

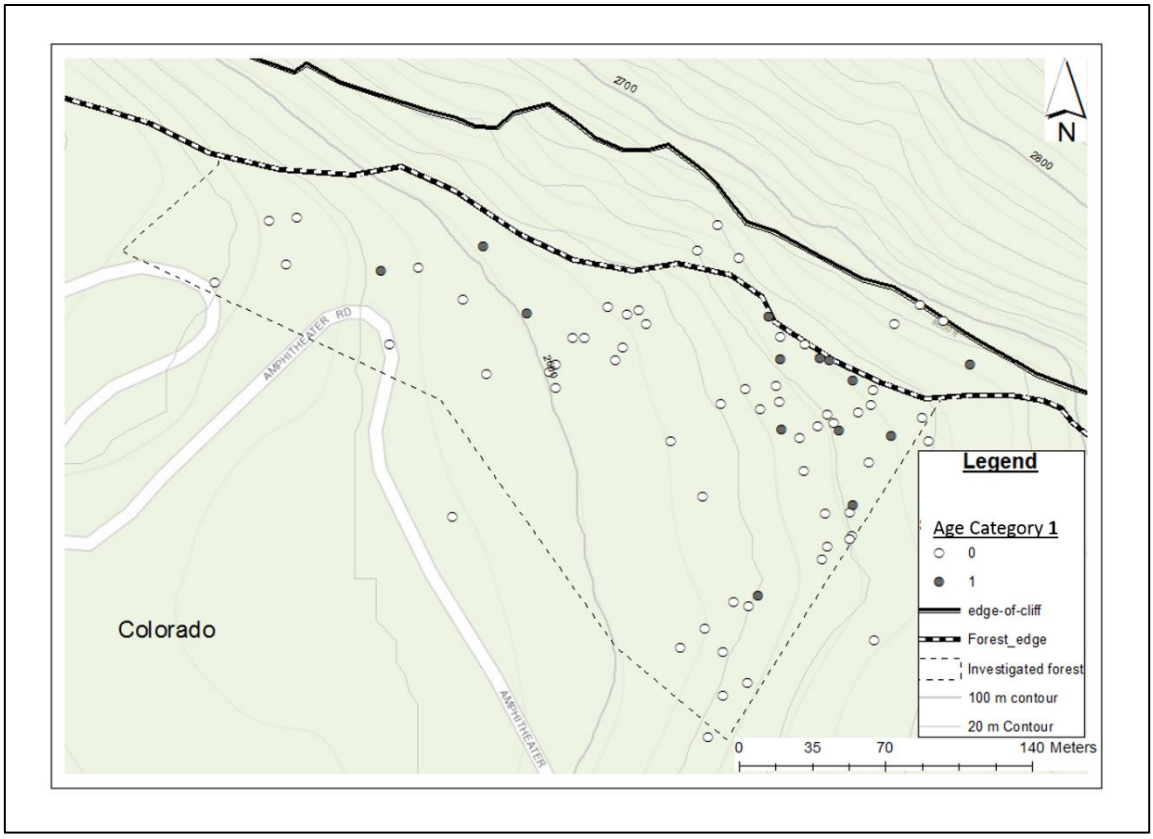

Figure 20 Location of fresh or recent injuries of 'category 1' (filled circles). Open circles denote all visible rockfall induced injuries

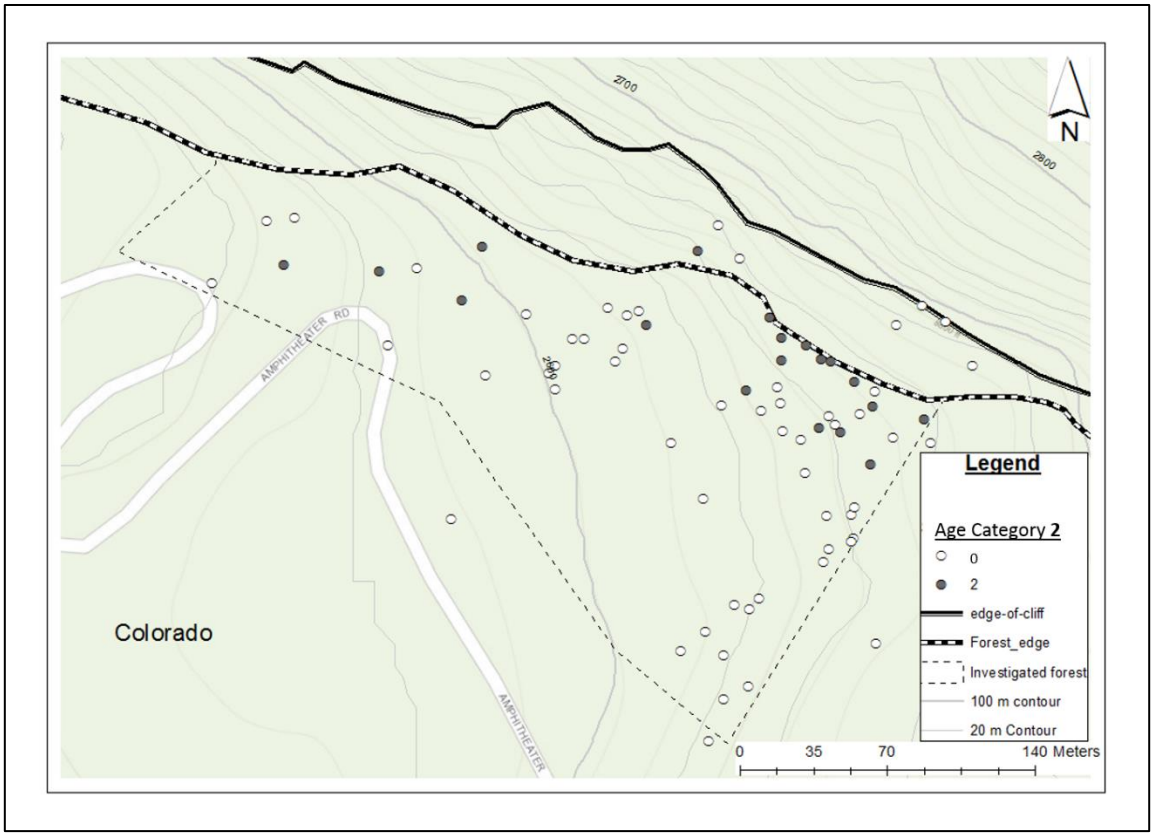

Figure 21 Location of partially recovered tree scars of 'category 2' (filled circles). Open circles denote all visible rockfall induced injuries

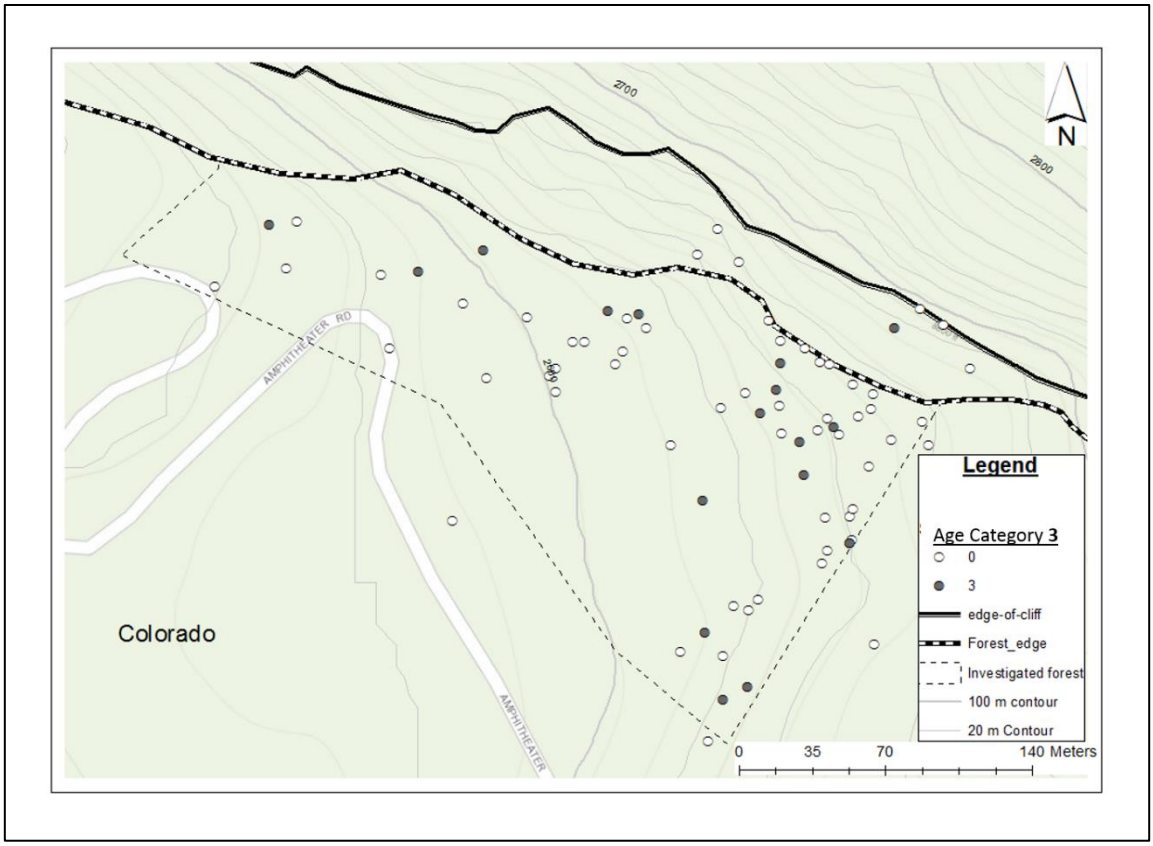

Figure 22 Location of old scars and injuries of 'category 3' (filled circles). Open circles denote all visible rockfall induced injuries

Rockfall deposits were categorized into five categories based on clast size (table 7). Figure 23 illustrates the spatial extent of the sampled rockfall deposits. Larger clasts are located near the upper limit of the forest where they are better sorted.

Table 7 Classification of rockfall deposits based on sample diameters. Grain size adapted from International grain size scale (ISO 14688-1: 2002)

category	classification	clast diameter (in)	clast diameter (mm)	count
1	soils	< 2.4	< 63	12
2	cobbles	2.4-7.8	63-200	19
3	small boulders	7.8-24.8	200-630	12
4	large boulders	24.8-60	630-1530	5
5	very large boulders	>60	>1530	5

The largest boulders traveled the farthest into the forest, however they are usually isolated and surrounded by soils (figure 24 A). The red line in figure 23, annotates the lower edge of the mapped talus and rockfall deposits and on average is about 70 m (230 ft) from the forest edge and about 100 m (328 ft) from the base of the cliff (figure 23). The exception to this is where flowing water has scoured channels in the forest floor and transported a heterogeneous mixture of debris downslope (figure 24 B, APPENDIX B4). Trees in direct contact with these debris flows were disregarded from this analysis.

Lichen cover was used to provide a separate, independent assessment of rockfall activity (table 8). The percent of cover of lichen on independent rock-fragment faces was amassed. The assumption is based on the saying “a rolling rock contains no moss”. In other words, if a rock fragment remains in place for an extended period of time, it will be covered with lichen. The lichen coverage can then be used as a surrogate for stability. Lichen growth is more extensive in the western part of the forest and generally is less abundant to the east (figure 25). Lichen growth can at time be sensitive to direct sunlight or extensive shade, however analysis of the sun’s movement and sunlight phases (Aqafonkin, 2009) indicate uniform sunlight spatially across the study area.

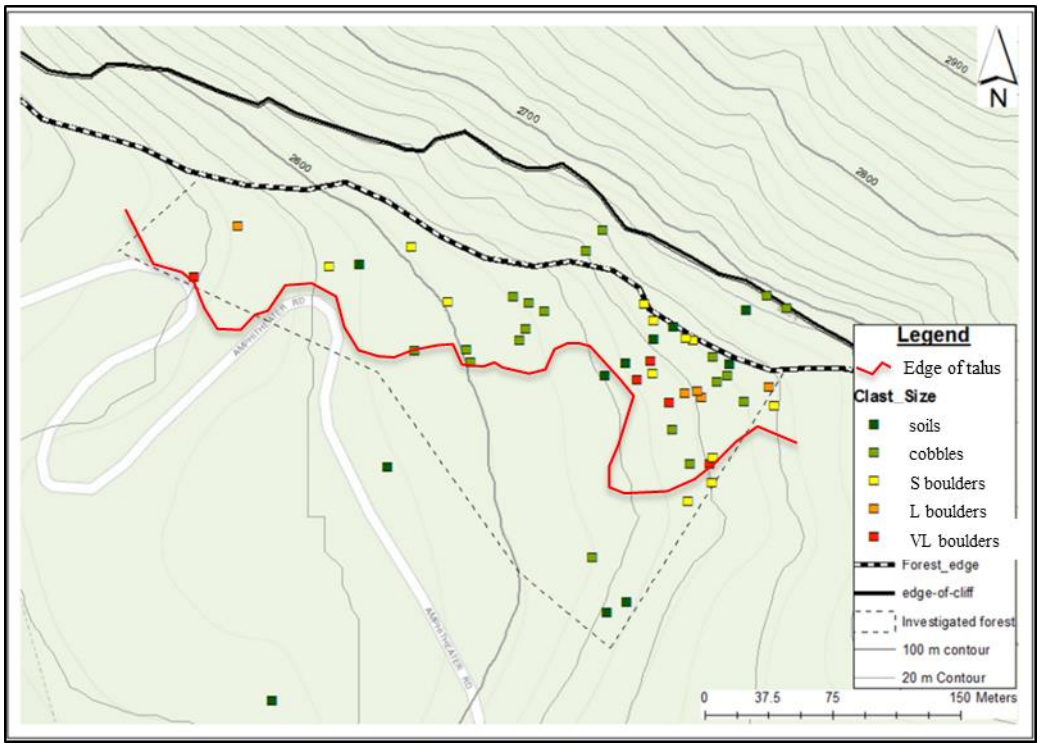

Figure 23 Locations of rockfall deposits subdivided into clast sizes (see Table 7 for more detail)

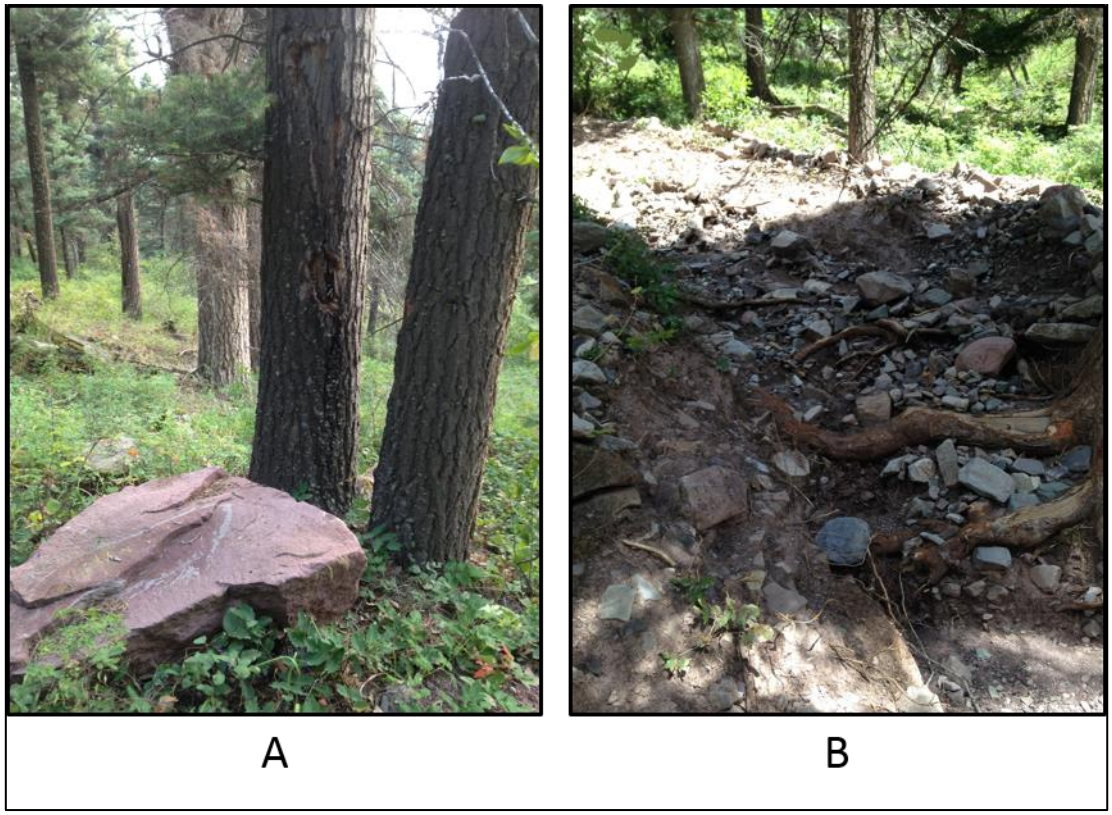

Figure 24 (A) Large isolated disc shaped boulder surrounded by vegetation/soil, and (B) active scouring of the slope transporting varying clast sizes down slope (Photos by Author)

Table 8 Classification of lichen colonization into three age categories based on relative age and percent coverage

category	classification	lichenometry (age)	description	count
1	young/recent	<15	little to no lichen growth	10
2	mixed	-	random distribution of clasts with >50% lichen cover, mixed with fresh blocks	16
3	old	>65	clasts with >50%	15

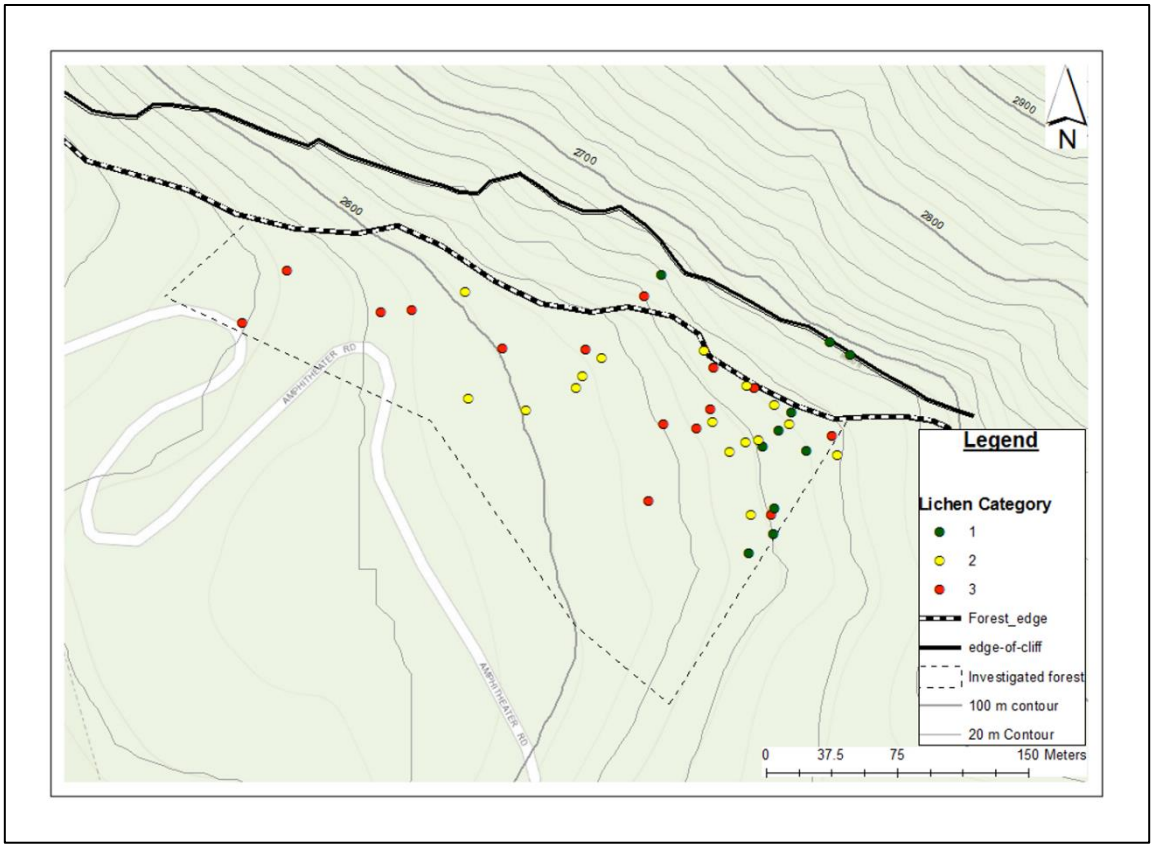

Figure 25 The spatial distribution of the lichen categories (see Table 8 for more details)

5.5 Rockfall Magnitude and Frequencies

During the period 1885-2015, rockfall activity continuously induced GD in the trees analyzed. Whereas multiple rockfall-induced GDs occurred during the same year, analysis of the sampled trees suggest rockfall activity consists of low magnitude-high frequency events for the time period.

5.6 Annual Variations in Rockfall Activity

Annual variability of rockfall was examined for the period 1885 to 2015 and, 121 GD, and an average of .93 GD year^{-1} in 20 trees (figure 26) was found. Additional

growth disturbances were identified in samples from older trees, however, because of the limited sample number of older trees, these were omitted from the analysis.

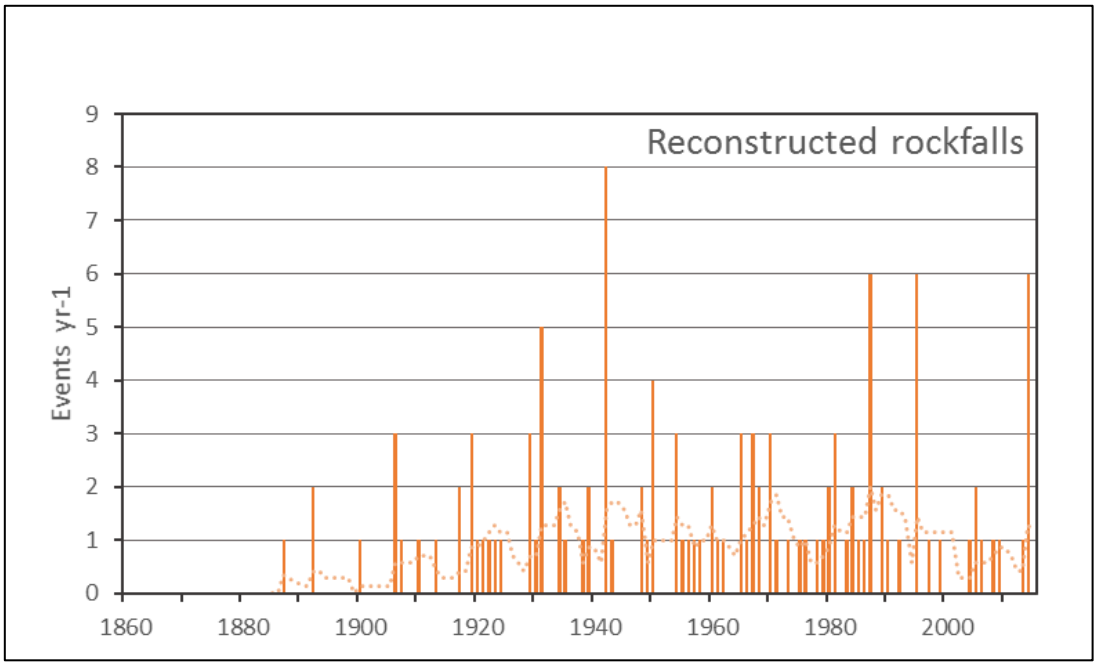

Figure 26 Reconstructed rockfalls based on analysis of GDs identified in tree cores (dashed line represents 7-year moving average)

Reconstruction of rockfall activity was limited to the last 105 years (1910-2015), as the number of samples were too small for the comparison of rockfall events prior to 1910. Investigation of yearly rockfall "rate" yielded an average of 0.30 events m^{-1} y^{-1} between 1910 and 2015 (STDEV: .45 events m^{-1} y^{-1}) ranging from zero to almost 5 events m^{-1} y^{-1}. Rockfall rates are slightly less continuous for the period of 1910-1925 as fewer trees existed, and the trees that did were younger with less exposed surface to record rockfall impacts (figure 27). The years during the period of 1926-1950 that are

perceived as having higher rockfall "rates" is a result of the limited number and nature of the trees sampled in this study. The absolute values of reconstructed rockfalls (figure 28) will provide better indication of the rockfall activity before 1951. As the tree ages, the increase in diameter makes the tree more likely to be impacted. This is demonstrated from the increased frequency of yearly rockfall "rates" after 1951. This result is similar to the results from (Stoffel et al., 2005b).

During the period 1926-1950 fewer years of rockfall activity were recorded; however, when present, several years experienced higher rockfall "rates". The number of years with rockfall events increased after 1951. The seven-year moving average, light-gray line shown in figure 28 does not show any significant trend, but rather demonstrates the continuous pattern of rockfall activity. Rockfall activity was difficult to detect at the turn of the 21st century and its implications will be discussed in more detail in the following chapter. Years with notable rockfall activity are 1931, 1942, 1950, 1960, 1965, 1970, 1981, 1987, 1995, 2005, and 2014.

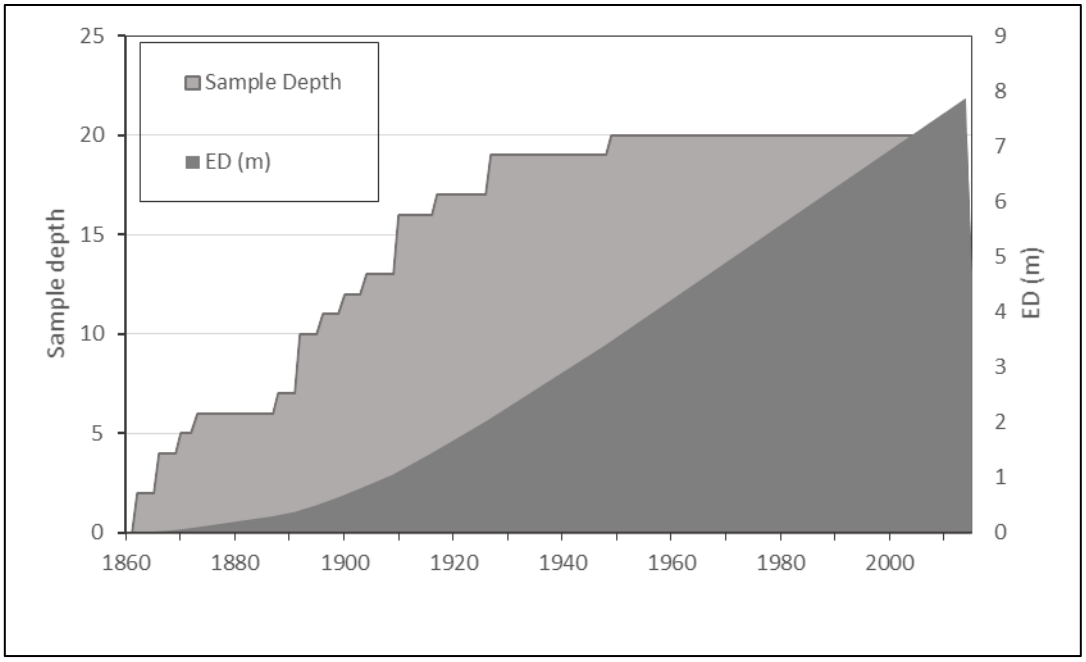

Figure 27 The light gray represents the available sample depth per year and the dark gray represents the exposed diameter for each year under investigation

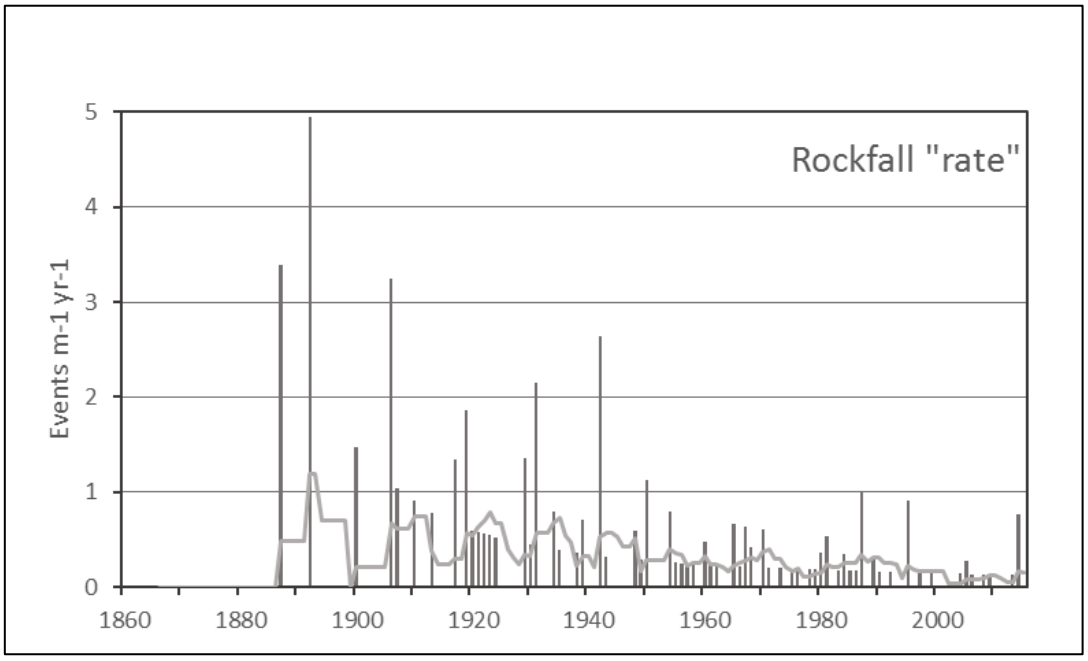

Figure 28 Rockfall 'rate' illustrated by the number of events $m^{-1}yr^{-1}$ (light-gray line represents 7-year moving average)

CHAPTER VI

DISCUSSION

This chapter recaps the analysis and discuss additional findings. The results are evaluated using all available published resources. In addition, this chapter discusses what the analysis means for the area and its potential application to similar areas.

6.1 Rockfall Chronology

A temporal chronology of rockfall activity was created using tree-core data. Rockfall activity was reconstructed from the GD observed in the tree-ring series of *Abies concolor* and a few *Pseudotsuga menziesii*.

6.1.1 Limitations

The predominate GD observed in the tree cores were injuries and the presence of adjacent callus tissue. These GD were easy to identify on fresh or recent injuries; however, it was more difficult on masked wounds and on recovered or overgrown scars. When older injuries have sufficient time to heal, they are difficult to detect on the exterior of the stem (Stoffel and Perret, 2006; Zielonka and Dubaj, 2009).

In addition, abrupt growth suppression and release was a common occurrence throughout the samples. This fact is likely because *Abies concolor* is highly responsive to annual climate fluctuations (Hurteau et al., 2007) and can create difficulties distinguishing annual increment responses from climate of geomorphic events (Tardif et al., 2003). The sensitivity of *Abies concolor* to climate might account for its limited use in dendrogeomorphic studies. In order to compensate for this issue, abrupt growth changes were only considered to be GD as response to rockfall, where unique growth

change was observed in years that it was uncharacteristic. Other studies of *Pinus sp*. and *Pinus hartwegii* also reported annual ring growth sensitivities to climate (Stoffel et al., 2008; Bollschweiler et al., 2010; Biondi, 2001; Biondi et al., 2003; Stoffel et al., 2011), however still proved to be an effective tree species for dendrogeomorphic use.

Identification of reaction wood was limited, likely because of how fast the energy is transferred from the impacting rock to the tree (fraction of a second) (Schneuwly and Stoffel, 2008). Another reaction to rockfalls that is not characteristic of *Abies concolor*, but has proved to be particularly reliable in rockfall studies is the timing of the formation of traumatic resin ducts (TRD) (Bollschweiler et al., 2008; Stoffel and Hitz, 2008; Schneuwly et al., 2009a; Stoffel and Corona, 2014). One TRD was observed in the 3 samples of *Pseudotsuga menziesii* (Douglas fir), however, four more were observed in the older section outside the period of analysis for this study and, therefore, were disregarded. This thesis demonstrates that, aside from prior noted limitations, *Abies concolor* (White fir) can be used in dendrogeomorphic assessments of rockfall activity.

The period for which rockfalls can be reconstructed is dependent on sample depth and the presence of visible or inferred injuries and associated GD. Rockfall reconstructions are therefore limited to the past 105 years and cannot provide a complete record for events that may have occurred earlier. Additionally, the number of rockfall reconstructions for the investigated study area represents an absolute minimum frequency. One reason for this is rock trajectories may or may not impact a tree during its decent thus only alluding to a partial record.

This study was conducted under strict reserve for the investigated forest. The number of trees to be sampled with an increment borer was limited and the extraction of cross-sections from standing tree stems or from felled trees or snags was not permitted. This restricted methodology prevented large sample number for a more detailed analysis of rockfall activity both spatially and temporally.

6.1.2 Evaluating Rockfall Activity

Rockfall activity is expressed at the rockfall "rate" which allows for a comparative assessment of the most recent events, when the exposed surface was the greatest, to earlier events when smaller DBH of younger trees made them less likely to be hit by a rockfall. The continuous nature of these GD for the period of 1910-2015 suggests low magnitude-high frequency rockfall events similar to the findings of (Stoffel et al., 2005b; Perret et al., 2006; Schneuwly and Stoffel, 2008; Stoffel et al., 2011). The injuries occurred primarily during different years suggesting they formed by separate isolated stones, which fell sporadically, rather than a large-scale event affecting many trees.

Low-magnitude high-frequency rockfall activity is typical of freeze-thaw cycles. Patterns of lichen cover showed a similar distribution (table 8). Climate data from the two data stations in Ouray show typical cycles during the Fall and Spring when temperatures drop below freezing followed by a brief warming period before returning to freezing conditions (APPENDIX D). This activity coupled with precipitation as either rain or snow facilitates the steep slopes and cliffs as prime areas for frost wedging and subsequent rockfall.

6.1.3 Notable Rockfall Activity

Notable years exhibiting abnormally high rockfall activity must then be examined as a result of some external factor 'promoting' and/or 'triggering' the rockfall event (i.e., abnormally high frost-thaw cycles, heavy rainfall or rapid snowmelt, extreme daily temperature fluctuations, winter storms or high wind events, earthquakes, ect.) (figure 29).

Years with notable rockfall activity are 1931, 1942, 1950, 1960, 1965, 1970, 1981, 1987, 1995, 2005, and 2014. When the exact triggering mechanism is unknown, investigation into significant documented events may provide more information on rockfall activity for that year. APPENDIX A contains the daily temperature and precipitation data for the notable years that occurred since 1965.

Weather data are unavailable for 1931 and 1942; however, the 1978 Floodplain Information Report for Ouray County reported flooding in 1931 (Ouray County, 2013). Rockfall activity in 1950 was denoted by suppression and injuries. Reports from SHELDUS show rapid snowmelt caused flooding. Runoff from meltwater could potentially dislodge rocks from the cliffs and slopes as either primary or secondary rockfall.

The largest recorded earthquake in Colorado's history occurred in the Montrose-Ridgeway area on October 11, 1960, as a magnitude 5.5. Damages were recorded in many of the surrounding cities, including Ouray. The intense shaking may have dislodged rocks or boulders on the steep slopes and cliffs surrounding Ouray and may be responsible for the injuries identified in this study. The GDs of 1965 can most likely be

attributed to the July cloudburst along Portland and Cascade Creeks (APPENDIX A2), which resulted in large debris flows and considerable flooding (Ouray County, 2013). In 1970, a small earthquake occurred on February 3, 1970, in San Miguel County, South of Norwood, as well as abnormally high precipitation during September of that year (APPENDIX A4). The years of 1980 and 1981 appeared to be ideal conditions for rockfall activity as considerable drought during the winter of 1980-1981 resulted in extremely dry soil and arid surface conditions. The dry and hard solid surface increased surface runoff when the area experienced a series of intense cloudbursts during the summer of 1981 (APPENDIX A5-A8). This resulted in extensive flooding and debris flows (Ouray, 2013). Rockfall analysis revealed numerous suppression and injuries in 1987 which is consistent with the type of growth response associated with large winter storm events such as those of that year (APPENDIX A9-A10). Significant events during 1995 include winter storms and the end of drought (APPENDIX A11-A12). Heavy rainfall on August 10 and 11, 2005, produced large-volume debris flows, and extensive flooding across Ouray (Ouray County, 2013). The year 2005 also experienced severe winter storms with temperatures nearly -10°. A massive rockslides was reported in January of 2014, which completely buried a portion of US 550, just outside of Ouray. The generally consistent growth release of healthy trees suggests decrease in competition as neighboring trees may be suffering from beetle infestation.

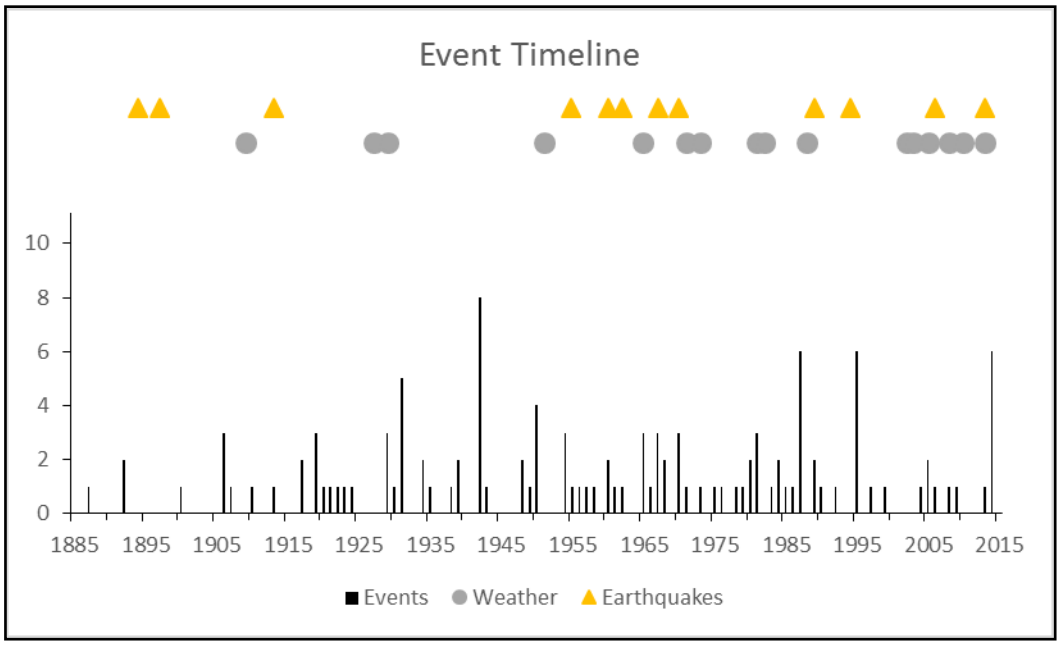

Figure 29 Event Timeline for rockfall occurrences and triggering mechanisms

6.2 Spatial Extent of Rockfall Activity

6.2.1 Rockfall Distribution

Analysis of recurrence intervals identified areas of preferred rockfall trajectories generally recording higher return periods of rockfalls (figure 30), and lower return periods on sampled trees protected by neighboring trees or located in a topographically favorable area. The number of trees affected by rockfall activity also decreases in a distant direction from the source highlighting the standard protective nature of the forest (Brang *et al.*, 2001) (APPENDIX B3). Recurrence intervals also align up with our mapped edge of our talus (figure 30).

One explanation for areas with higher recurrence intervals is the size and number of trees along the upper boundary of the forest edge. Those trees are likely to record the

highest number of impacts as compared to those down slope, thus rightfully named "Centurion trees". Areas with higher recurrence intervals also correspond to areas with debris flows. These areas are down slope from major gullies as gullies can act as a major conduit for rockfall debris (APPENDIX B5).

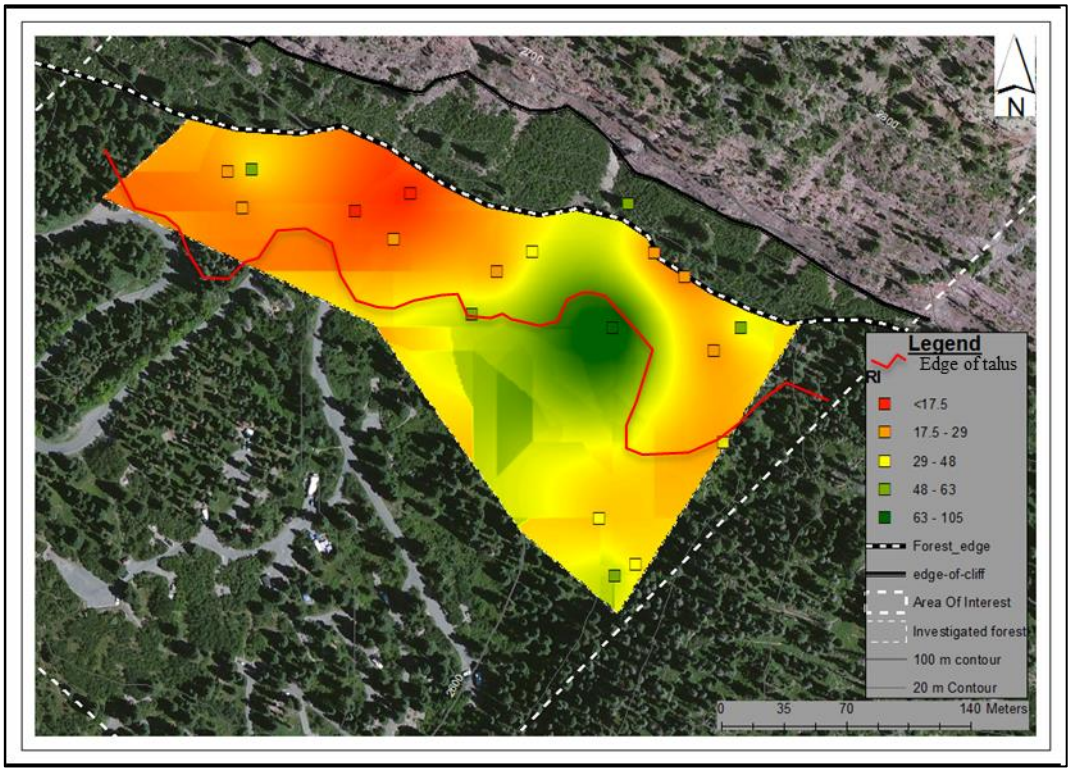

Figure 30 Distribution of return periods for rockfalls with interpolated values. The red line indicates the mapped lower edge of talus and rockfall deposits.

The distribution of clast size and sorting reflected the variable nature of a random rockfall process. Many of the largest boulders came to rest at the base of trees, which ended its downward momentum after being slowed by decapitated trees upslope. The

injuries visible from these impacts were used to help gage the frequency of rocks that make in deeper into the protective forest stand.

Figure 31 is a histogram of the number of total injuries binned into distances from forest edge. There is a strong negative correlation, and notice the abrupt brake between the 60 and 80 m which fits with the 70 m previously identified. This illustrates that the number of rockfall injuries will be the highest towards the leading edge of the forest as more rocks will impact trees before coming to a rest. The larger rocks that travel farther may impact multiple trees along its path thus demonstrating the frequency of recorded rockfall impacts with distance into the forest and not the number of individual rockfall events.

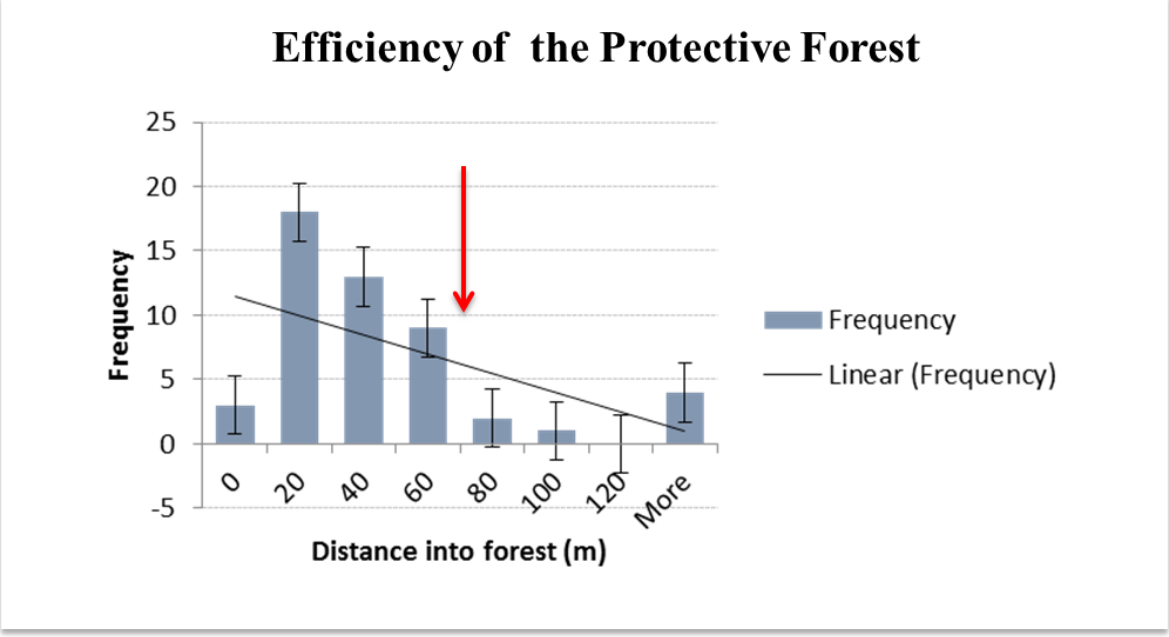

Figure 31 Histogram of number of total injuries binned into distances from forest edge. This illustrates that the farther into the forest, away from the source, the fewer impacts will be recorded as rocks are more likely to come to rest upslope (error bars and linear trend annotated)

6.2.2 Broader Impacts

For the past three years, the *Abies concolor* surrounding Ouray have been subjected to an engraver beetle infestation. Rapid removal of the forest will remove vital protective cover. This study can serve as a basis for planners who may want to create an educational program through awareness. Trees that are closely spaced will act as a protective barrier to rockfall, however, the higher density of trees in an area may also promote the spread of engraver beetles. Future work should place controls on tree spacing for optimal forest protection and limiting beetle outbreak.

CHAPTER VII

CONCLUSION

7.1 Conclusions and Recommendations

A US forest service campground is positioned below a large bedrock escarpment and is subjected to rockfall hazards. This research answers the question: What are the spatial and temporal characteristics of rockfall? To answer this question, two objectives were established. (i) delineate the spatial patterns of rockfall activity and (ii) establish a temporal chronology of rockfall activity. By visually analyzing rockfall deposits, rockfall induced tree injuries and associated growth disturbances to *Abies concolor* (White fir) trees, this study was able to delineating areas of varying rockfall hazard potential. The findings identify the area with the greatest hazard to rockfall activity is the area located below the gullies of the overlying cliffs and steep slopes. Additionally, the area from the base of the cliff to the forest edge, often called the scree slope, is especially subjected to rockfalls. Rockfalls activity continue into the adjacent forested zone, however, rockfall deposits were observed to rarely travel greater than 70 m once they enter the protective forest boundary, suggesting that the current spacing and density of the forest acts as an effective protective forest to rockfalls.

This study also demonstrates that tree-ring records of *Abies concolor* (White fir) can be used in geomorphic analysis to infer spatial and temporal patterns of rockfall event. This may be beneficial to other alpine areas where *Abies concolor* is the dominant tree species in the forest. Analysis of growth defects identified from *Abies concolor* tree cores allowed for the reconstruction of a rockfall chronology. This reconstruction

alluded to the observation of rockfall activity being dominated by low magnitude, high frequency events. Also, for the time period of investigation (1910-2015), no large mass movement event occurred within the study area. Based on the previous observations, we interpret the recorded rockfalls as attributed to annual freeze and thaw activity.

Although there were no observations of a large-scale mass movement event, several years recorded abnormally high rockfall rates, as determined from the reconstructed rockfall chronology. Years with abnormal rockfall activity include 1931, 1942, 1950, 1960, 1965, 1970, 1981, 1987, 1995, 2005, and 2014. Notable years exhibiting abnormally high rockfall activity are a result of some additional external factor 'promoting' and/or 'triggering' the rockfall event. Such external factors observed include heavy rainfall, rapid snow melt, earthquakes, among others.

Future work should include a hazard rating systems such as the "RHRS" which can be modified to categorize hazardous slope conditions on the steep slopes and cliffs above the campground. Maps can be produced using GIS software to visualize which lithologies and specific areas present the greatest hazard to slope failure.

Those hazards can then be used as a tool in rockfall modeling softwares to model rockfall trajectories based on expected release zones. Further work can also be used to predict rockfall velocities, and bounce heights using tree scar heights, and clast size, shape, and composition.

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APPENDIX A

DAILY TEMPERATURE AND PRECIPITATION

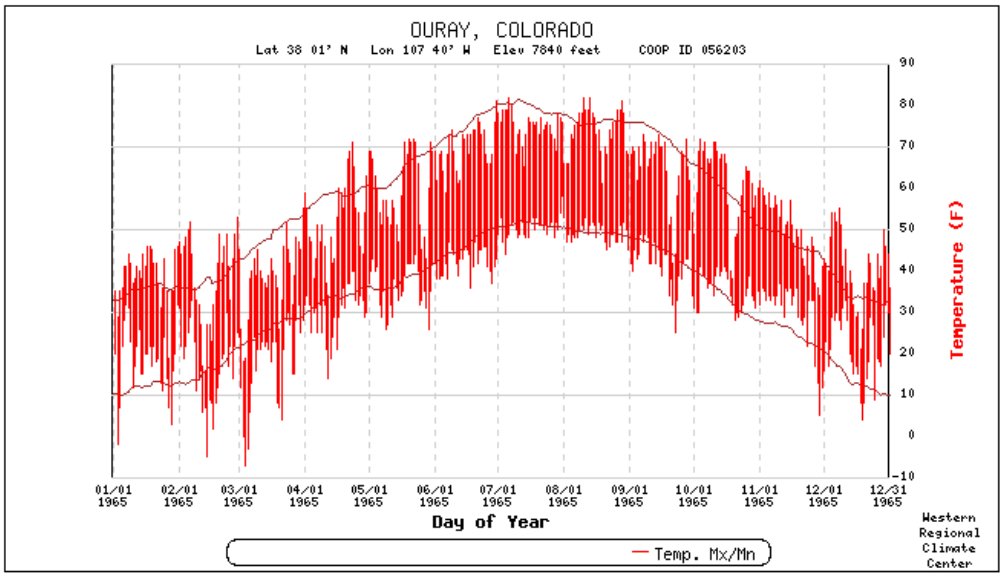

Figure A1: Daily temperature (F°) for 1965 (Source: Western Regional Climate Center)

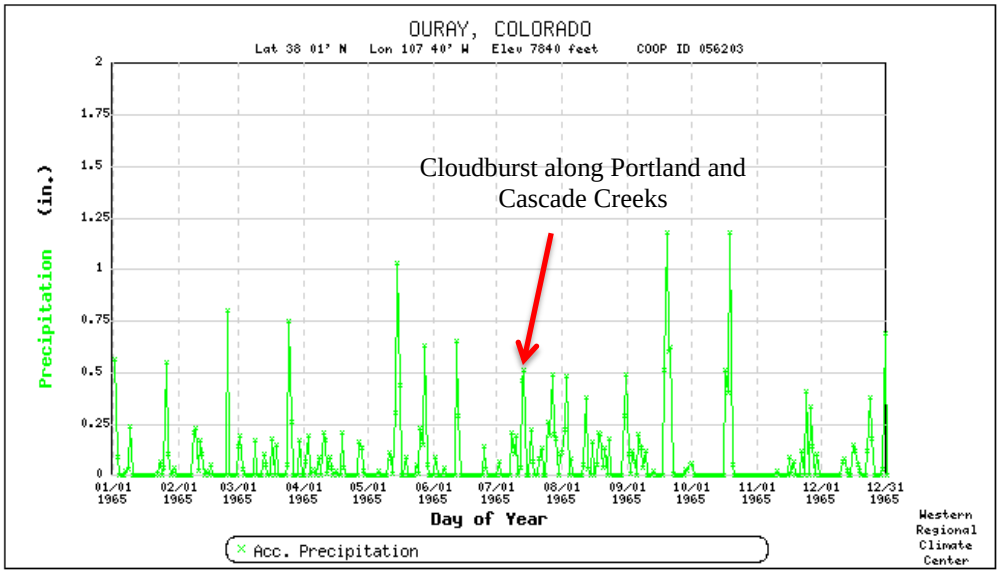

Figure A2: Daily precipitation (in) for 1965 (Source: Western Regional Climate Center)

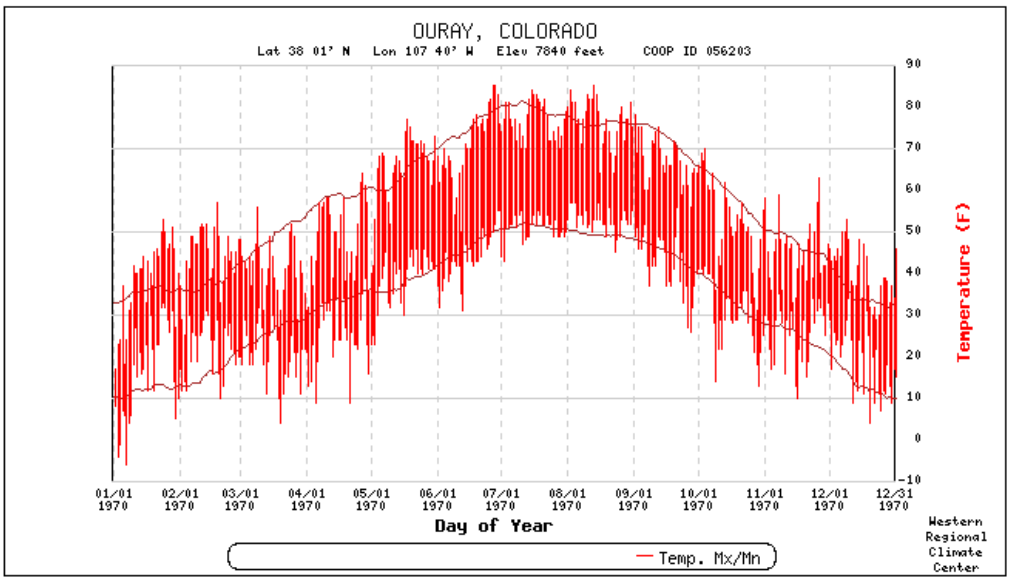

Figure A3: Daily temperature (F°) for 1970 (Source: Western Regional Climate Center)

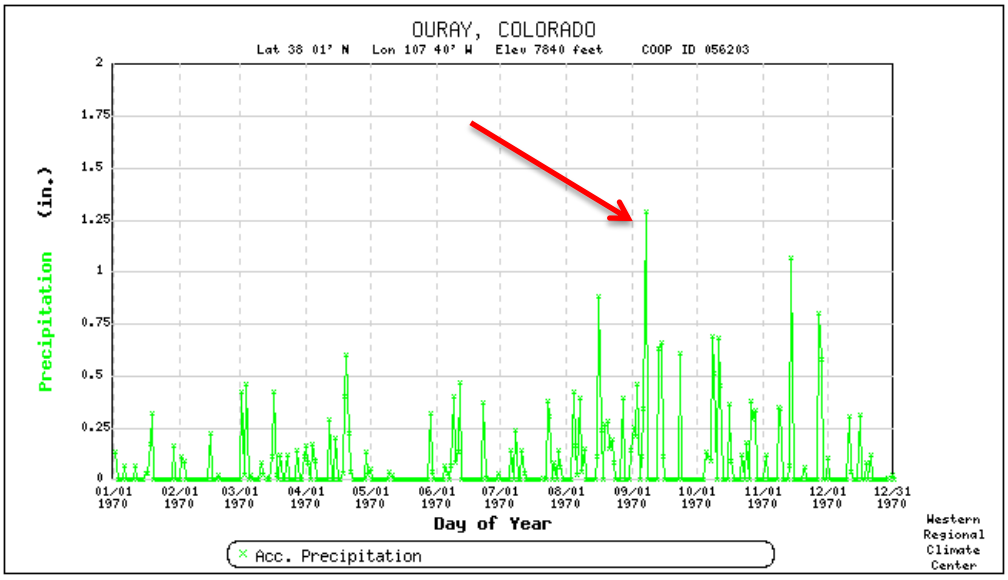

Figure A4: Daily precipitation (in) for 1970 (Source: Western Regional Climate Center)

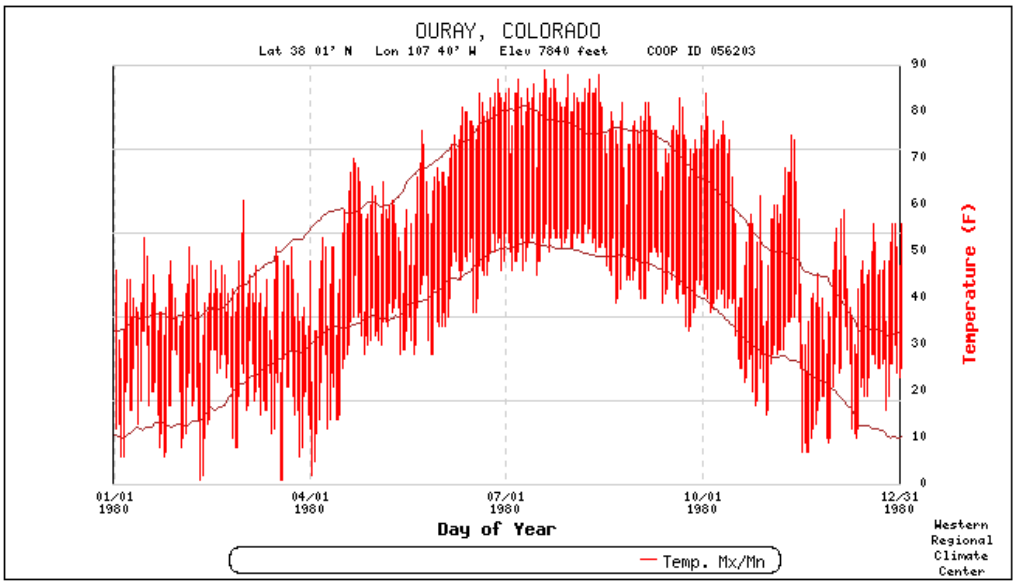

Figure A5: Daily temperature (F°) for 1980 (Source: Western Regional Climate Center)

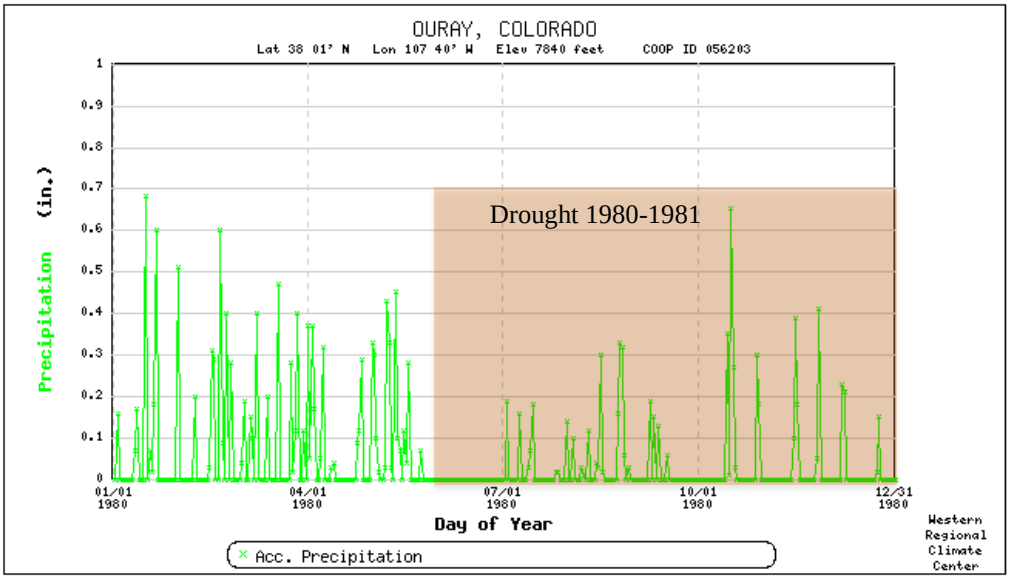

Figure A6: Daily precipitation (in) for 1980 (Source: Western Regional Climate Center)

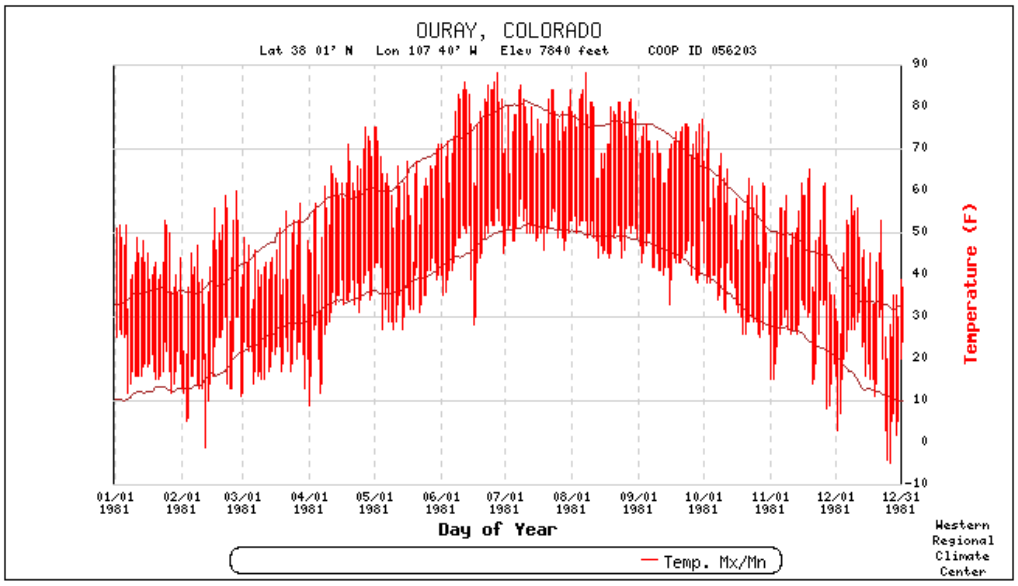

Figure A7: Daily temperature (F°) for 1981 (Source: Western Regional Climate Center)

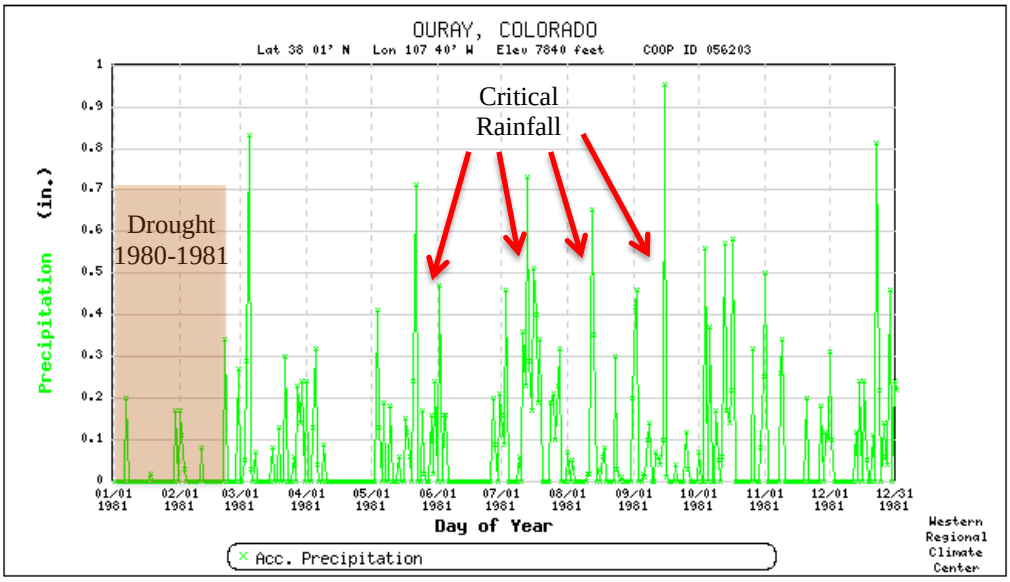

Figure A8: Daily precipitation (in) for 1981 (Source: Western Regional Climate Center)

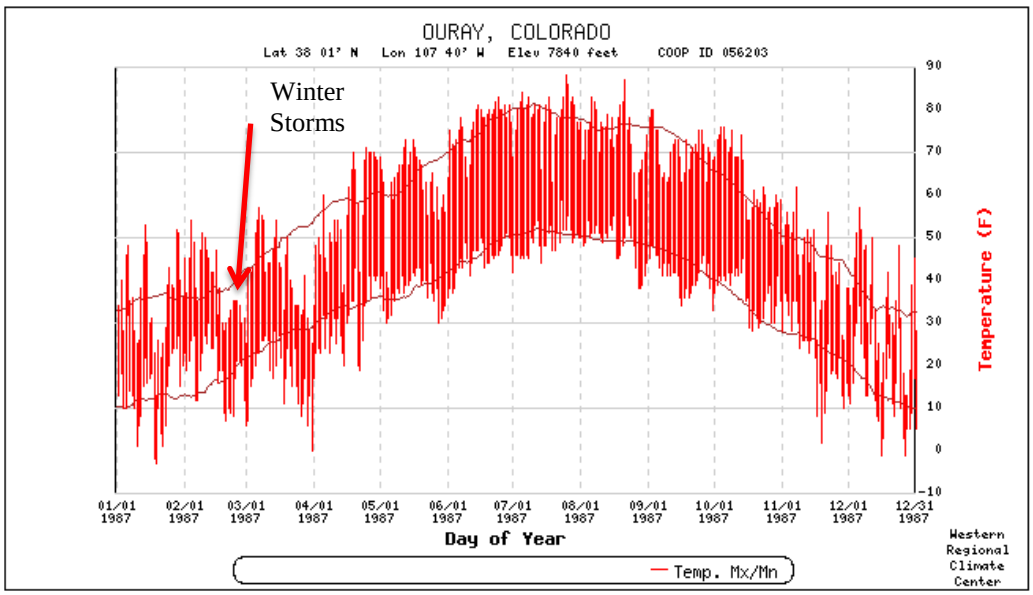

Figure A9: Daily temperature (F°) for 1987 (Source: Western Regional Climate Center)

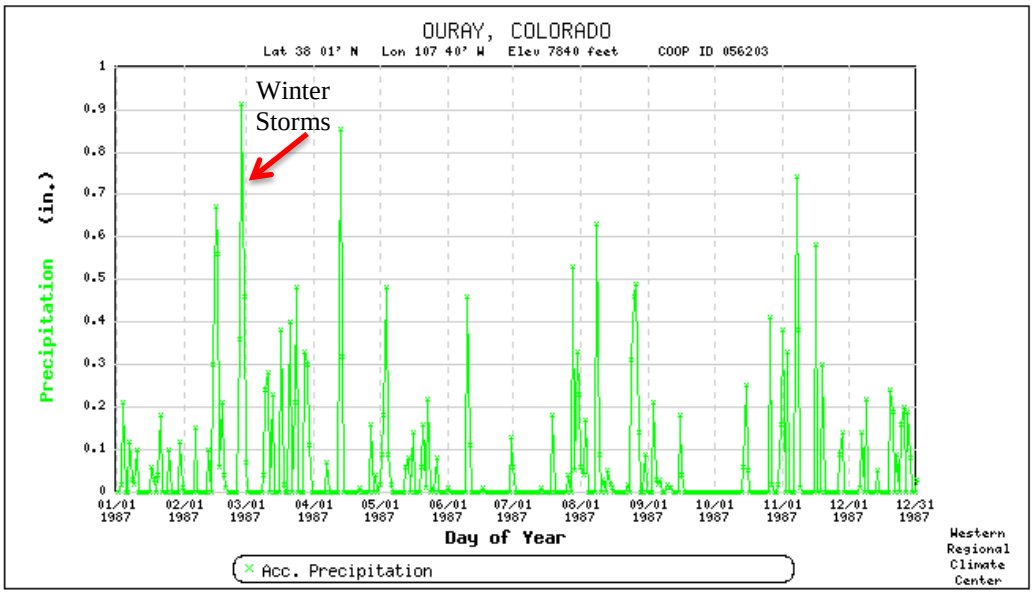

Figure A10: Daily precipitation (in) for 1987 (Source: Western Regional Climate Center)

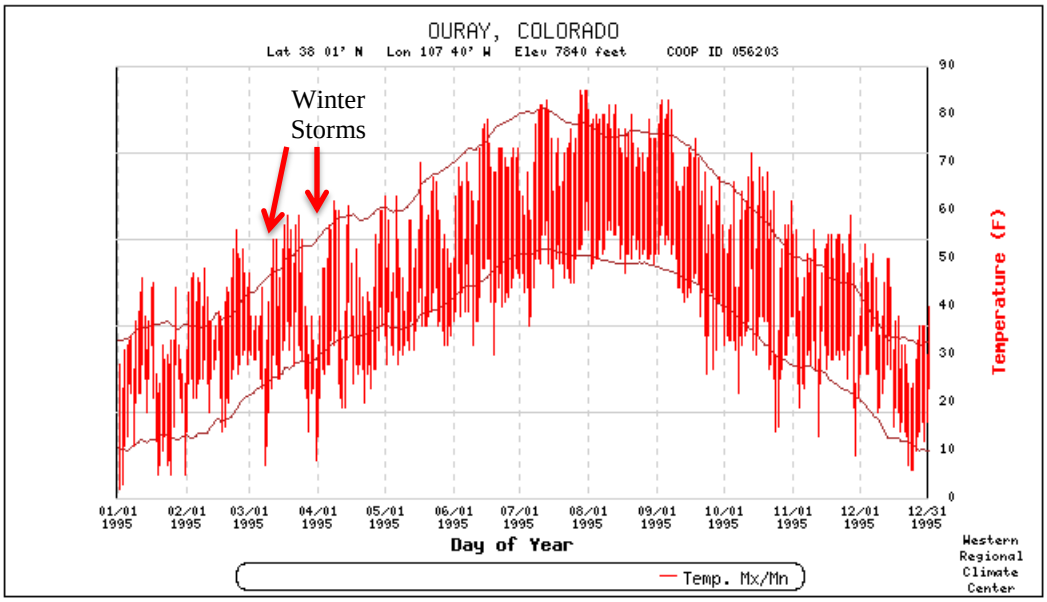

Figure A11: Daily temperature (F°) for 1995 (Source: Western Regional Climate Center)

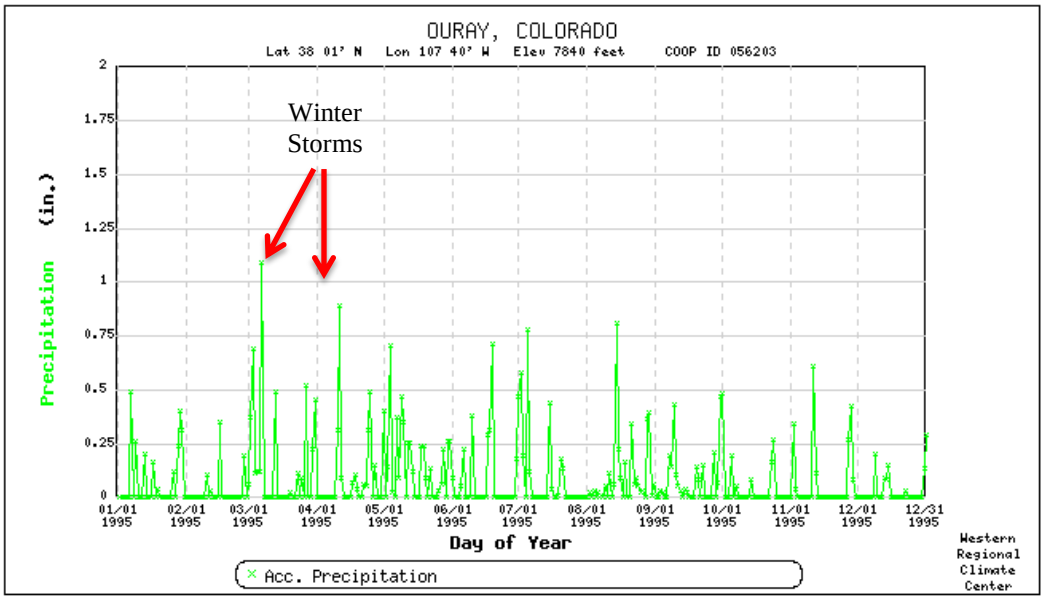

Figure A12: Daily precipitation (in) for 1995 (Source: Western Regional Climate Center)

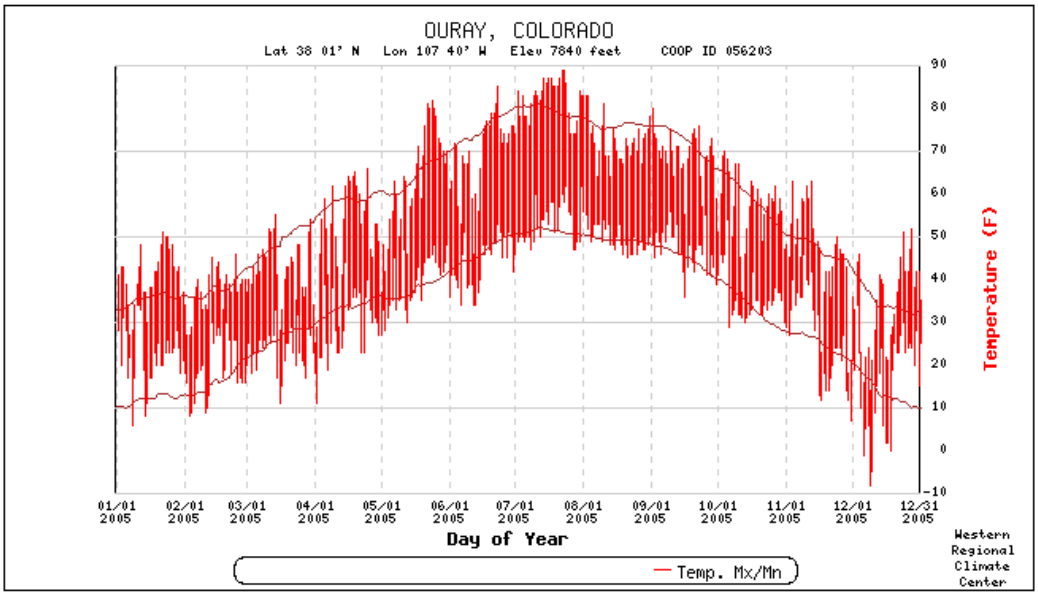

Figure A13: Daily temperature (F°) for 2005 (Source: Western Regional Climate Center)

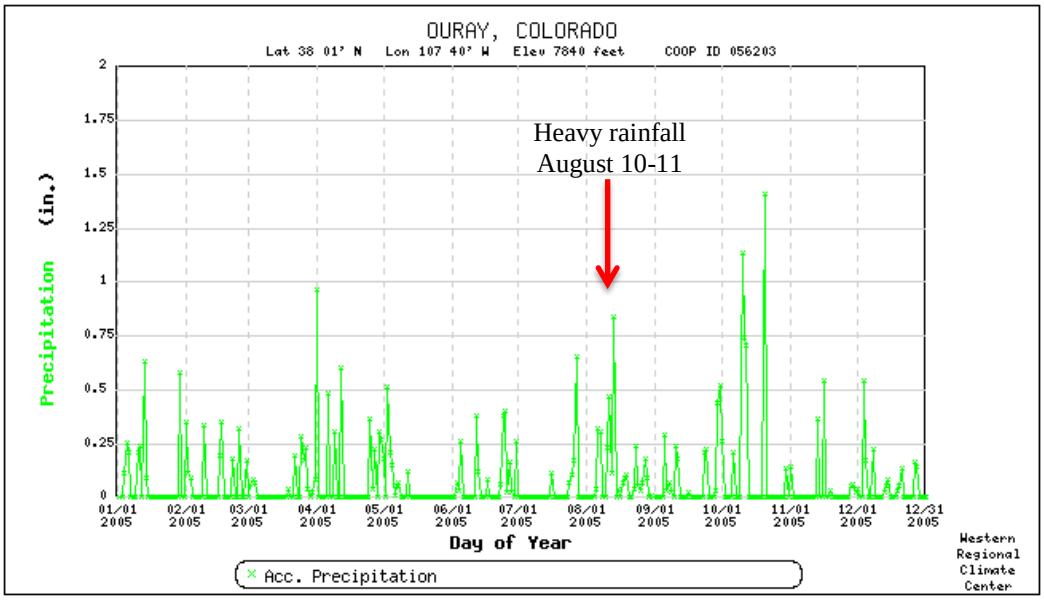

Figure A14: Daily precipitation (in) for 2005 (Source: Western Regional Climate Center)

APPENDIX B

ADDITIONAL FIGURES

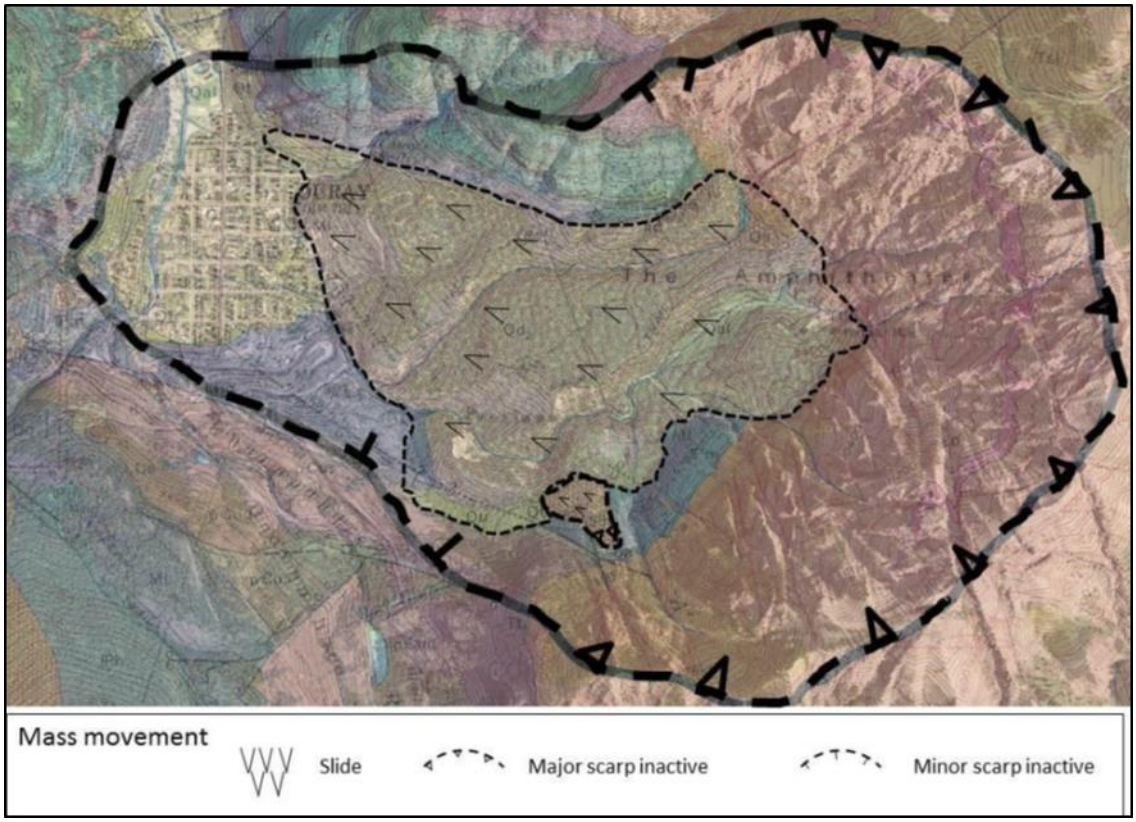

Figure B1: Ouray Amphitheater landslide deposits from (from Reed, 2013)

Figure B2: Mosaic of injured trees (Photos by author)

Table B1: Average rockfall distance from forest edge in each category

Age Category	Average distance (m)
1 (2000-2015)	29.2
2 (1950-2000)	18.8
3 (<1950)	56.8
Total average	~35

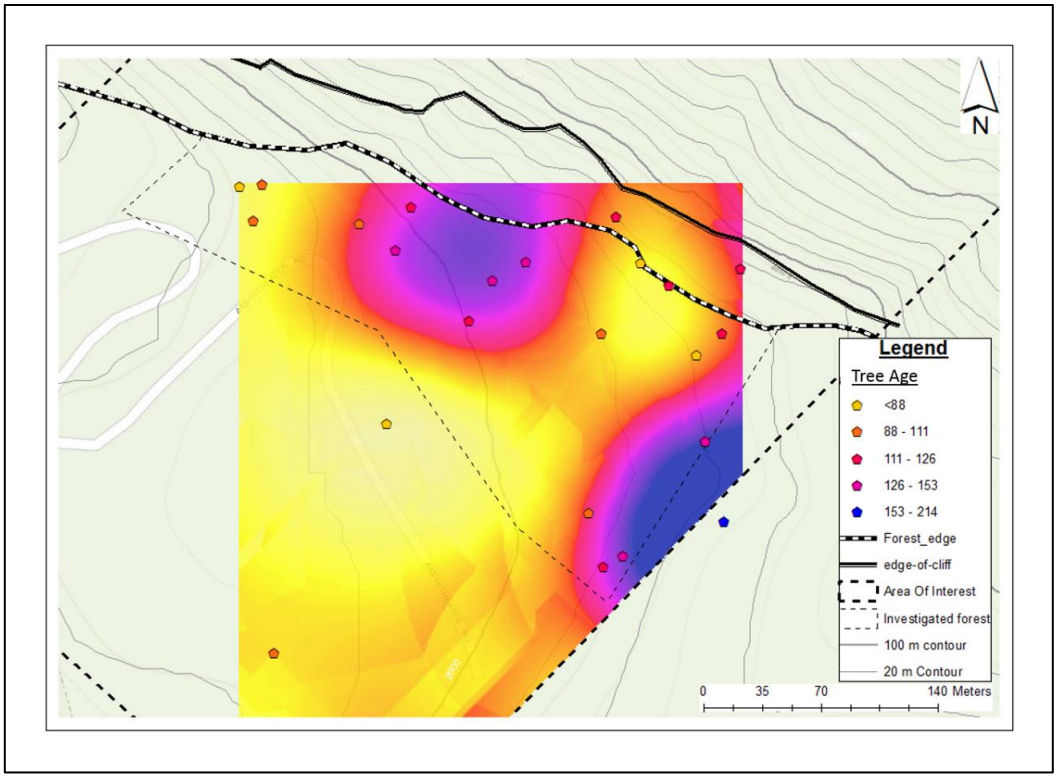

Figure B3: Visualization of tree ages with interpolated values

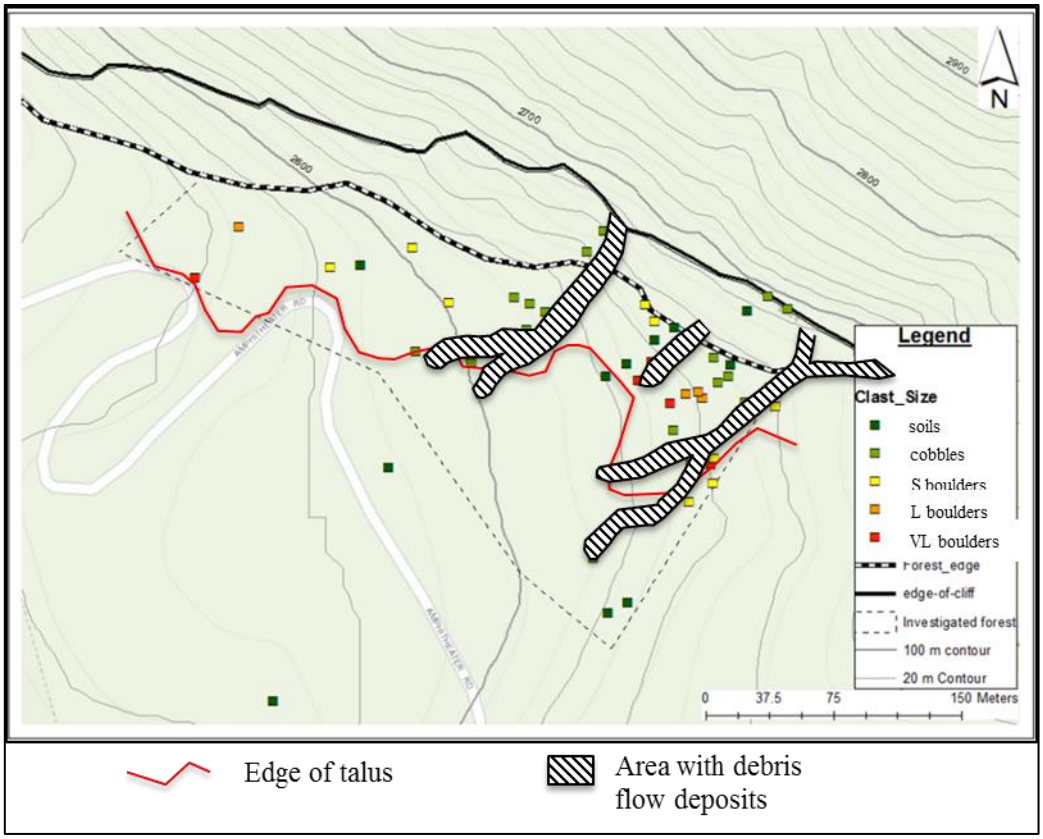

Figure B4: Locations of rockfall deposits subdivided into clast sizes. Redline annotates the lowed edge of the mapped talus debris. Areas with debris flows are also shown.

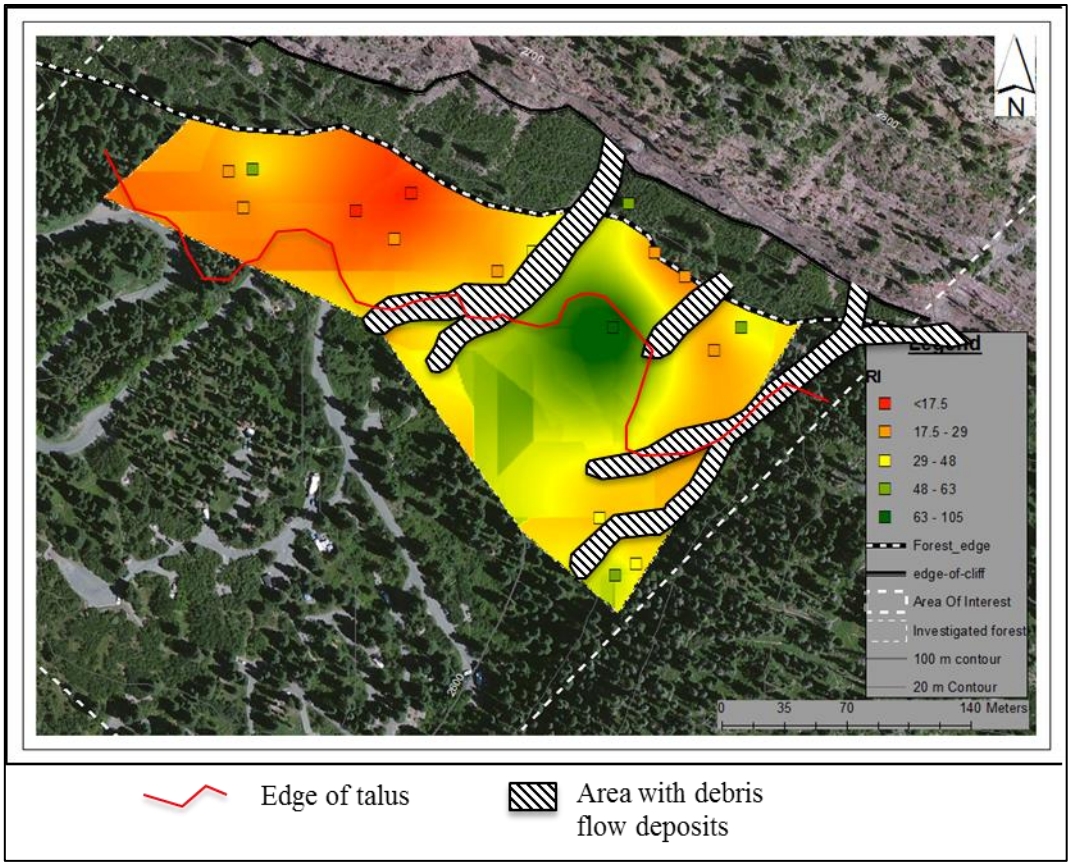

Figure B5: Distribution of return periods for rockfalls with interpolated values. Redline annotates the lowed edge of the mapped talus debris. Areas with debris flows are also shown.

APPENDIX C

RETURN PERIOD DATA

Table C1: Estimation of return periods of rockfalls, depending on the availability of growth disturbances in trees

Tree	First ring	Age (years)	Tree diameter	Impacts	Return period (years)
O1501	1904	111	21.3	2	55.5
O1502	-	-	27.4	-	-
O1503	1910	105	57.9	3	35.0
O1504	-	-	-	-	-
O1505	1900	115	48.8	2	57.5
O1506	-	-	12.2	-	-
O1507	1890	125	61.0	1	-
O1508	1892	123	39.6	6	20.5
O1509	1949	66	30.5	3	22.0
O1510	1892	123	48.8	2	61.5
O1511	1873	142	30.5	5	28.4
O1512	1910	105	48.8	1	105.0
O1513	-	-	-	-	-
O1514	1927	88	30.5	4	22.0
O1515	1892	123	48.8	9	13.7
O1516	1917	98	27.4	4	24.5
O1517	1862	153	15.2	7	21.9
O1518	1910	105	30.5	6	17.5
O1401	1900	114	32.0	4	-
O1402	1910	104	57.9	2	-
O1403	1928	86	54.9	2	-
O1404	1800	214	57.9	3	-
O1405	1866	148	31.1	6	24.7
O1406	1866	148	31.1	4	37.0
O1407	1870	144	64.0	3	48.0
O1408	1896	118	57.9	2	59.0
O1409	1927	87	16.5	3	29.0
O1410	1936	78	63.1	-	-
O1411	1909	105	63.1	4	-
O1412	1916	98	48.8	4	-
O1413	1862	152	37.8	4	38.0
O1414	1888	126	68.0	2	63.0
Total	-	-	-	98	-
Mean	-	118.0	42.1	3.6	39.2

Note: Return periods were obtained by dividing tree age (years) by the number of reconstructed impacts. Tree diameter (cm) taken at breast height.

APPENDIX D

ADDITIONAL WEATHER DATA

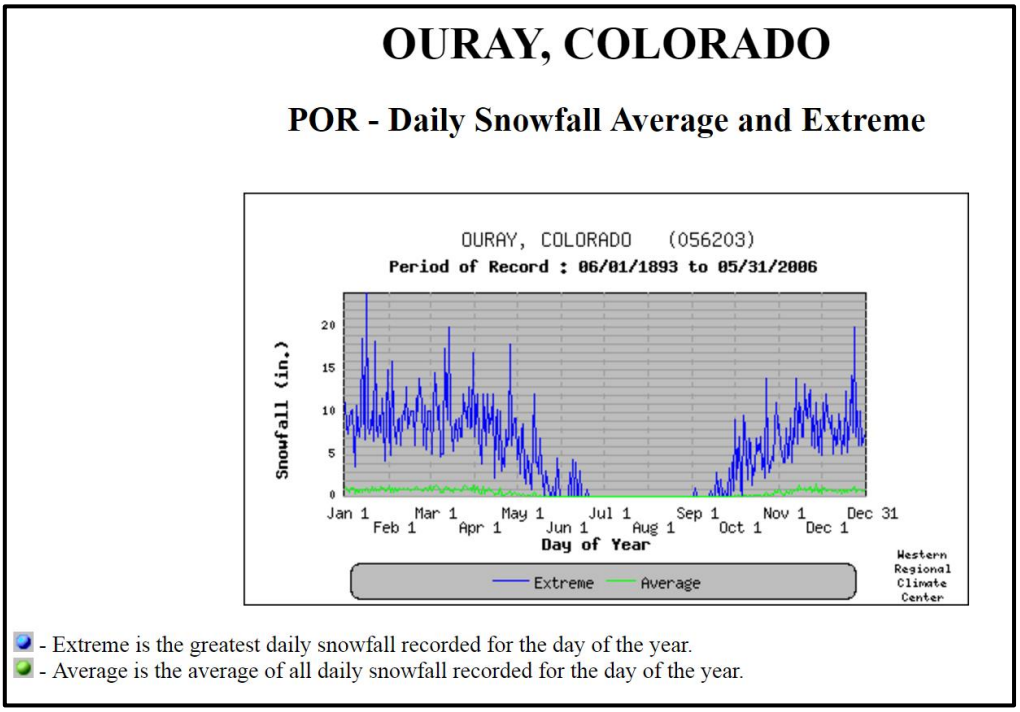

Figure D1: Ouray, Co., daily snowfall average and extreme (1893-2006) (Source: Western Regional Climate Center)

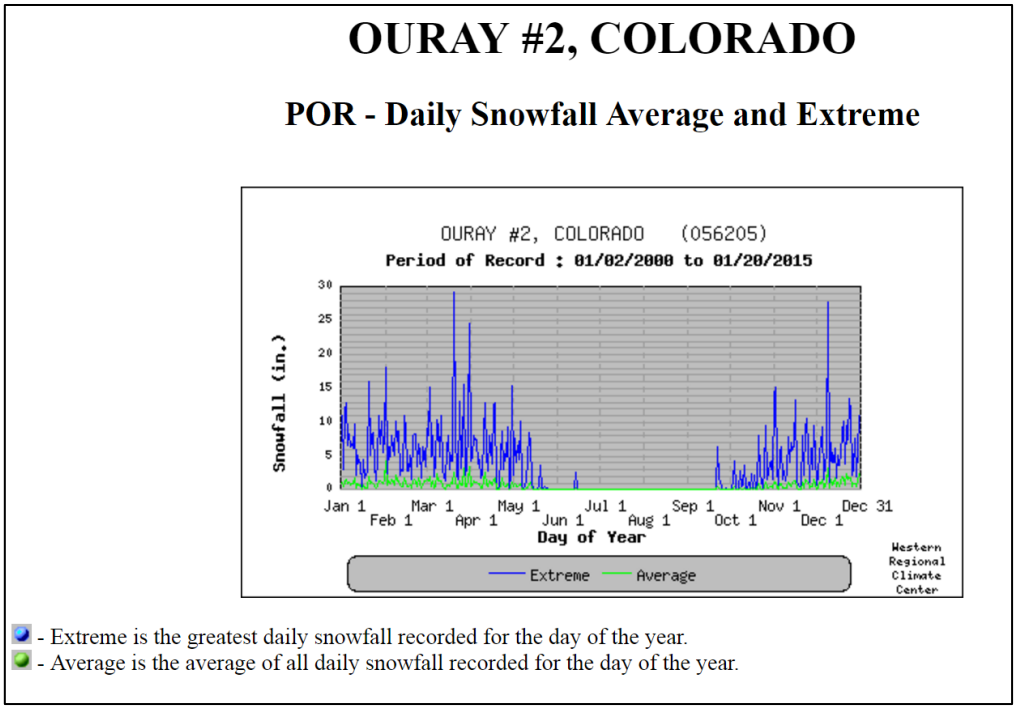

Figure D2: Ouray, Co., daily snowfall average and extreme (2000-2015) (Source: Western Regional Climate Center)

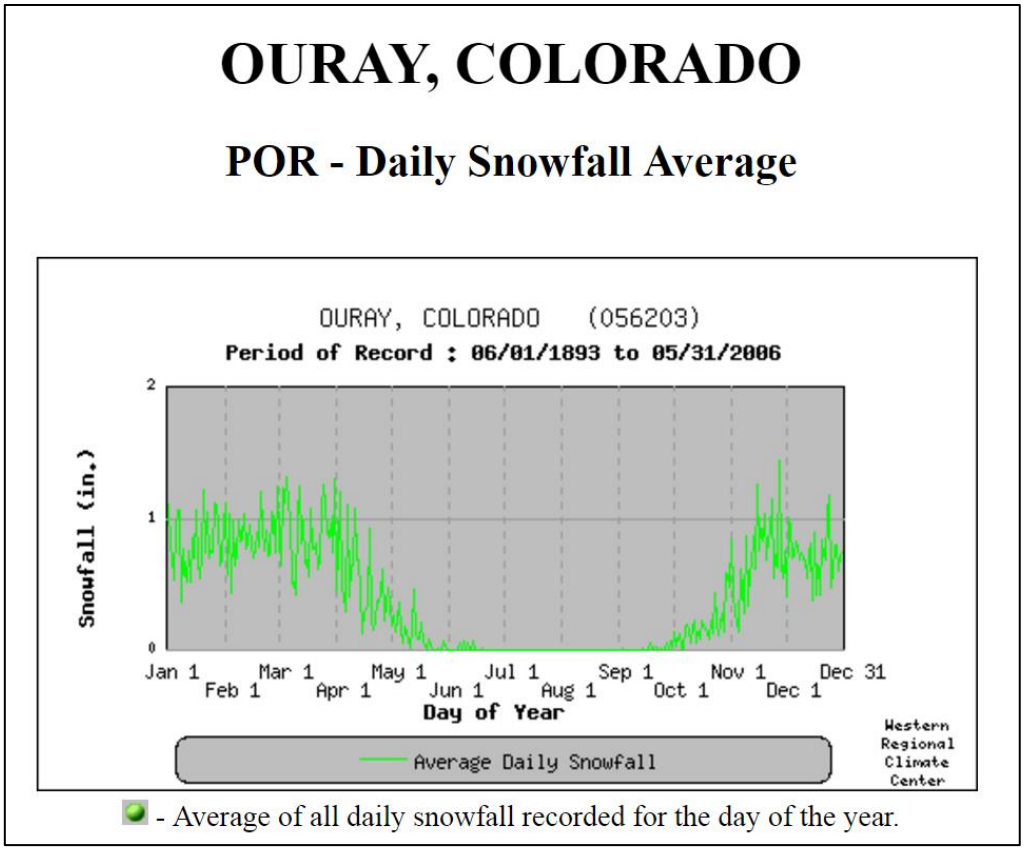

Figure D3: Ouray, Co., daily snowfall average (1893-2006) (Source: Western Regional Climate Center)

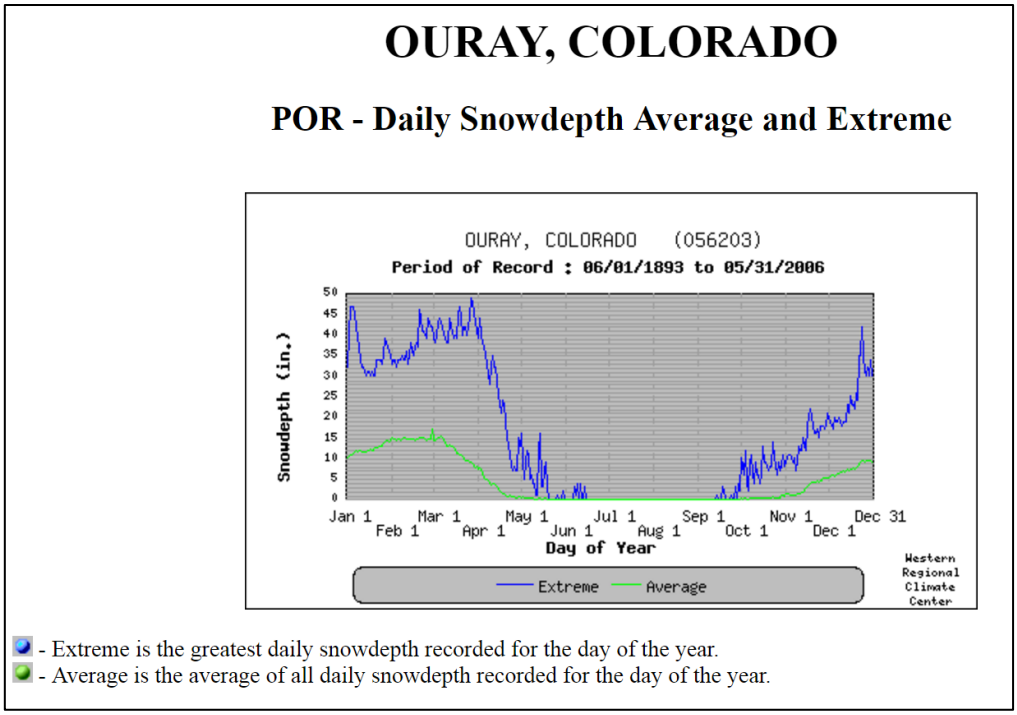

Figure D4: Ouray, Co., daily snowdepth average and extreme (1893-2006) (Source: Western Regional Climate Center)

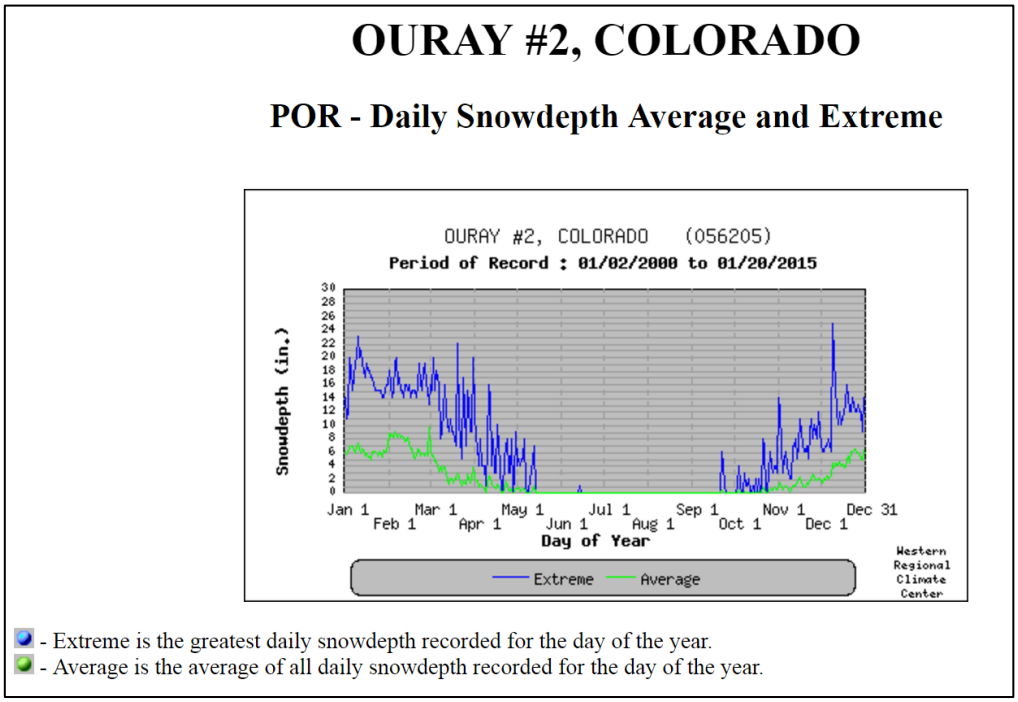

Figure D5: Ouray, Co., daily snowdepth average and extreme (2000-2015) (Source: Western Regional Climate Center)

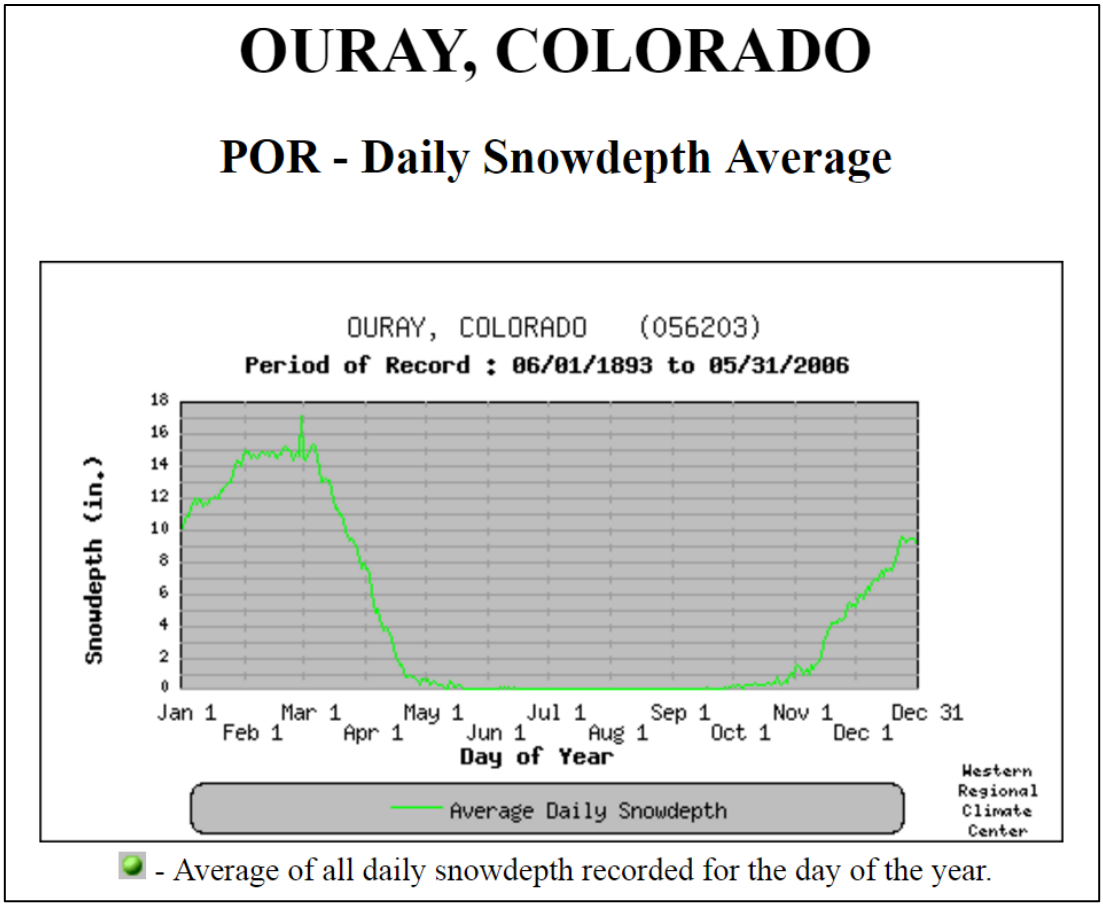

Figure D6: Ouray, Co., daily snowdepth average (1893-2006) (Source: Western Regional Climate Center)

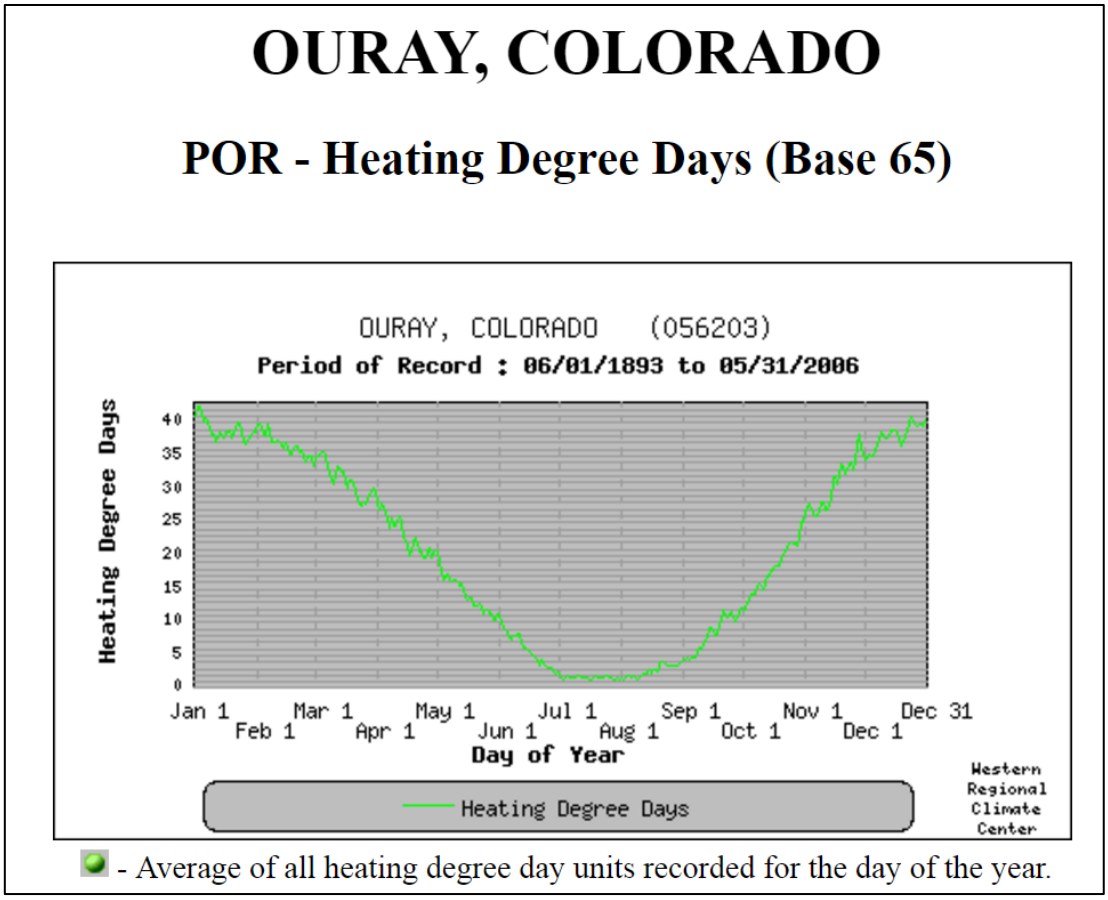

Figure D7: Ouray, Co., heating degree days (1893-2006) (Source: Western Regional Climate Center)

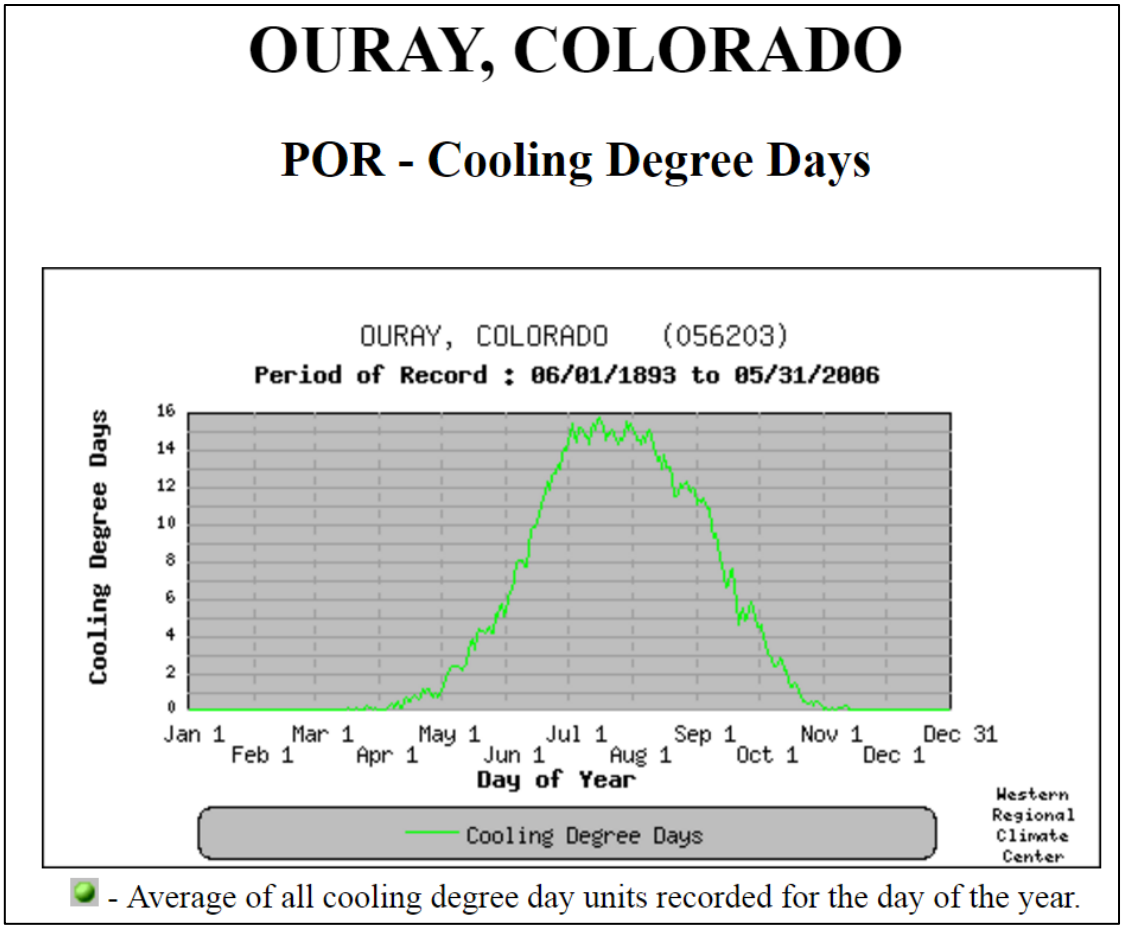

Figure D8: Ouray, Co., cooling degree days (1893-2006) (Source: Western Regional Climate Center)

APPENDIX E

COFECHA RESULTS

```
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Program COF  21:33  Fri 25 MAR 2016  Page   1
 []
 []  P R O G R A M     C O F E C H A
Version 3.00P    29671
 ---------------------------------------------------------------------------------------
----------------------------------------

 QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 Title of run:           cores8 omitted

 File of DATED series:   Cores8

 CONTENTS:

    Part 1:  Title page, options selected, summary, absent rings by series
    Part 2:  Histogram of time spans
    Part 3:  Master series with sample depth and absent rings by year
    Part 4:  Bar plot of Master Dating Series
    Part 5:  Correlation by segment of each series with Master
    Part 6:  Potential problems: low correlation, divergent year-to-year changes, absent
rings, outliers
    Part 7:  Descriptive statistics

 RUN CONTROL OPTIONS SELECTED                          VALUE
```

```
         1  Cubic smoothing spline 50% wavelength cutoff for filtering
                                                          32 years
         2  Segments examined are                         50 years lagged successively by
25 years
         3  Autoregressive model applied                   A  Residuals are used in master
dating series and testing
         4  Series transformed to logarithms               Y  Each series log-transformed
for master dating series and testing
         5  Critical correlation, 99% confidence level   .3281
         6  Master dating series saved                     N
         7  Ring measurements listed                       N
         8  Parts printed                            1234567
         9  Absent rings included in master series         N

 Time span of Master dating series is  1800 to  2015   216 years
 Continuous time span is               1800 to  2015   216 years
 Portion with two or more series is    1862 to  2015   154 years

   >> WARNING:  Year  1800 absent in    1 of    1 series; Master Series value  -.037
   >> WARNING:  Year  1952 absent in    1 of   40 series; Master Series value   .285
   >> WARNING:  Year  1953 absent in    1 of   40 series; Master Series value   .689
   >> WARNING:  Year  1955 absent in    1 of   41 series; Master Series value   .321
   >> WARNING:  Year  1957 absent in    1 of   41 series; Master Series value   .998
   >> WARNING:  Year  1958 absent in    2 of   41 series; Master Series value   .743
   >> WARNING:  Year  1959 absent in    2 of   41 series; Master Series value  -.331
   >> WARNING:  Year  1960 absent in    2 of   41 series; Master Series value   .315
   >> WARNING:  Year  1962 absent in    2 of   41 series; Master Series value   .498
   >> WARNING:  Year  1965 absent in    1 of   41 series; Master Series value  1.331
   >> WARNING:  Year  1966 absent in    1 of   42 series; Master Series value   .253
   >> WARNING:  Year  1968 absent in    1 of   42 series; Master Series value   .681
   >> WARNING:  Year  1969 absent in    1 of   42 series; Master Series value   .306
   >> WARNING:  Year  1970 absent in    1 of   42 series; Master Series value   .092
   >> WARNING:  Year  1974 absent in    1 of   42 series; Master Series value   .924
```

```
  >> WARNING:  Year  1975 absent in    1 of   41 series; Master Series value   .996
  >> WARNING:  Year  1983 absent in    1 of   41 series; Master Series value  1.444
  >> WARNING:  Year  1984 absent in    1 of   41 series; Master Series value  1.077
  >> WARNING:  Year  1994 absent in    1 of   40 series; Master Series value  -.341
  >> WARNING:  Year  1995 absent in    1 of   40 series; Master Series value   .862
  >> WARNING:  Year  1996 absent in    2 of   40 series; Master Series value   .034
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  >> WARNING:  Year  2000 absent in    2 of   40 series; Master Series value   .058
  >> WARNING:  Year  2001 absent in    2 of   40 series; Master Series value  -.258
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  >> WARNING:  Year  2007 absent in    3 of   38 series; Master Series value   .626
  >> WARNING:  Year  2009 absent in    1 of   38 series; Master Series value   .661

                                      ****************************************
                                      *C* Number of dated series        42 *C*
                                      *O* Master series 1800 2015  216 yrs *O*
                                      *F* Total rings in all series   4187 *F*
                                      *E* Total dated rings checked   4125 *E*
                                      *C* Series intercorrelation     .669 *C*
                                      *H* Average mean sensitivity    .374 *H*
                                      *A* Segments, possible problems    7 *A*
                                      ****************************************

 ABSENT RINGS listed by SERIES:           (See Master Dating Series for absent rings listed
by year)

 D1_2_1B     1 absent rings:   1993
 3_32Aab     1 absent rings:   2003
 D1_52A      5 absent rings:   1958  1959  1960  1961  1962
 D1_21C      3 absent rings:   1994  1995  1996
```

```
 S&L 1        3 absent rings:   1981  1983  1984
 S&L 4A       3 absent rings:   2006  2007  2008
 L 4A         1 absent rings:   2006
 L 4B         1 absent rings:   2006
 S4A          2 absent rings:   1974  1975
 S&L5B        3 absent rings:   1991  1992  1993
 S&L6D       20 absent rings:   1951  1952  1953  1954  1955  1956  1957  1958  1959  1960
1961  1962  1963  1964  1965  1966
                                1967  1968  1969  1970
 34Aab        1 absent rings:   1800
 4234B       11 absent rings:   1999  2000  2001  2002  2003  2004  2005  2006  2007  2008
2009
 4234A       11 absent rings:   1998  1999  2000  2001  2002  2003  2004  2005  2006  2007
2008
 41_33Bab     1 absent rings:   1996

            67 absent rings   1.600%
```

```
 ------------------------------------------------------------------------------------------
----------------------------------------
 1000      1100      1200      1300      1400      1500      1600      1700      1800
1900      2000             Beg   End

Ident    Seq year year  Yrs
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :
:    :    : -------- --- ---- ---- ----
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
<=========== 4235Aabc   2 1898 2014  117
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
<========== D1_2_1B    3 1907 2014  108
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
. <======== 1_33Aab    4 1928 2014   87
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
<============ 3_3_1_A    5 1885 2013  129
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
<========== 3_32Aab    6 1900 2014  115
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
.  <======= 4131Aabc   7 1936 2014   79
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
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<========== D1_21C     9 1906 2014  109
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
. <=======> D3_33B    11 1929 2006   78
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
.    <===== 42_35B    12 1954 2014   61
```

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.    .<==== L3         16 1966 2015   50
<=========== S4 B       17 1892 2015  124
.   <====== S&L 4A     18 1949 2015   67
.   <=====> S&L 4B     19 1949 2002   54
.    <===== S&L 4C     20 1951 2013   63
. <======== L 4A       21 1925 2015   91
<=========== L 4B       22 1893 2015  123
<============ L5          23 1873 2015  143
.<========= OK 1A      24 1917 2015   99
.<========= OK 1B      25 1910 2015  106
<========== Basecamp   26 1904 2015  112
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.<========= Pb1A       28 1917 2015   99
. <======== Pb1B       29 1927 2015   89
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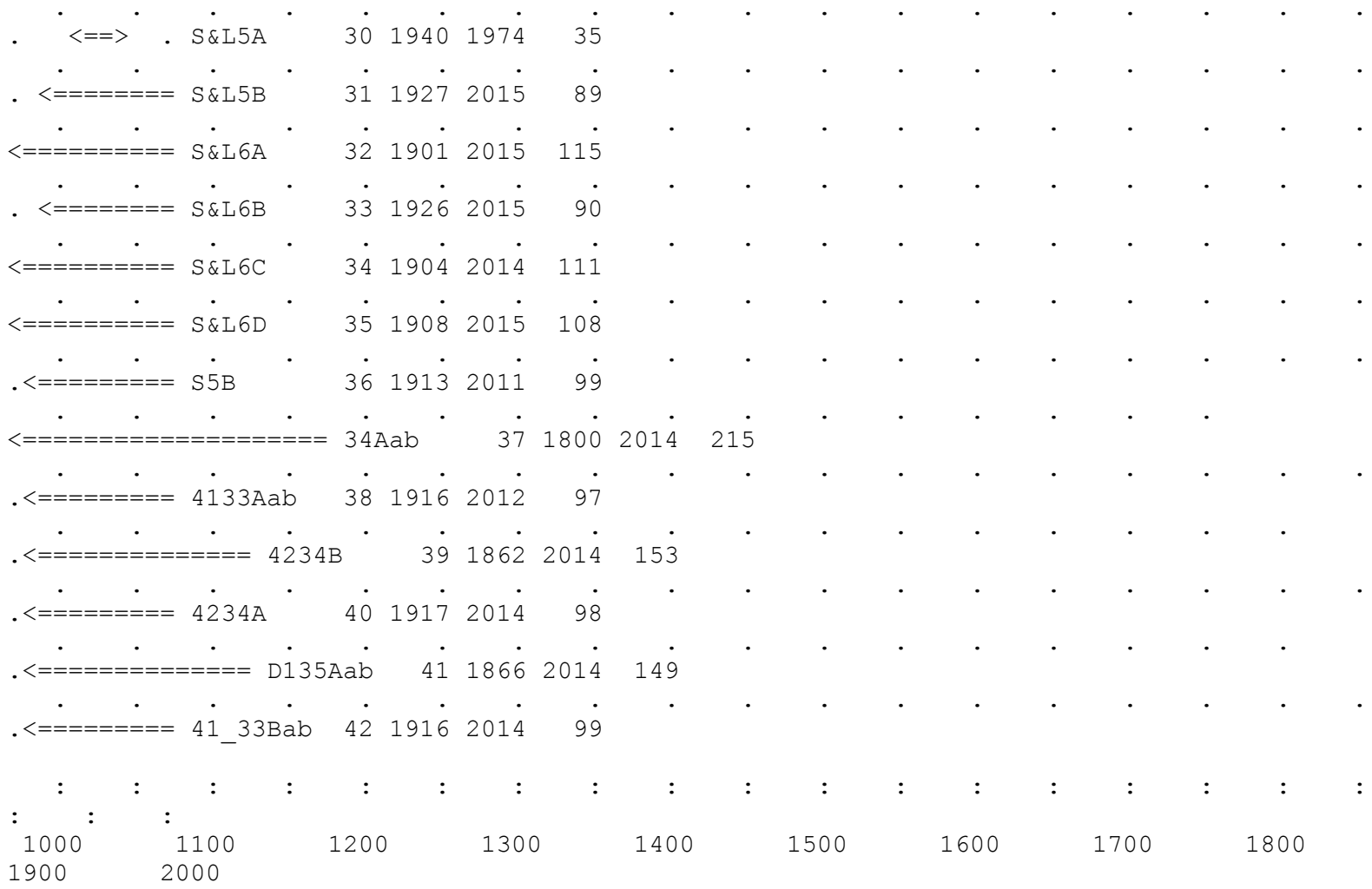
S&L5A 30 1940 1974 35
S&L5B 31 1927 2015 89
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S&L6B 33 1926 2015 90
S&L6C 34 1904 2014 111
S&L6D 35 1908 2015 108
S5B 36 1913 2011 99
34Aab 37 1800 2014 215
4133Aab 38 1916 2012 97
4234B 39 1862 2014 153
4234A 40 1917 2014 98
D135Aab 41 1866 2014 149
41_33Bab 42 1916 2014 99
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

PART 3: Master Dating Series: cores8 omitted
21:33 Fri 25 MAR 2016 Page 3

Year	Value	No Ab		Year	Value	No Ab		Year	Value	No Ab		Year	Value	No Ab	
1900	-.155	9		1950	-.739	39		1800	-.037	1	1<<	1850	1.134	1	
1901	.150	10		1951	-1.958	40	1	1801	.148	1		1851	-3.274	1	
1902	-1.704	10		1952	.285	40	1<<	1802	1.099	1		1852	.292	1	
1903	.431	10		1953	.689	40	1<<	1803	.662	1		1853	.475	1	
1904	-.627	14		1954	-2.035	41	1	1804	.870	1		1854	.830	1	
1905	-.668	14		1955	.321	41	1<<	1805	.581	1		1855	.145	1	
1906	.650	15		1956	-1.184	41	1	1806	-.554	1		1856	-1.207	1	
1907	1.270	16		1957	.998	41	1<<	1807	1.185	1		1857	.232	1	
1908	.176	17		1958	.743	41	2<<	1808	1.262	1		1858	1.100	1	
1909	.370	18		1959	-.331	41	2<<	1809	-.614	1		1859	.572	1	
1910	-.334	19		1960	.315	41	2<<	1810	-1.382	1		1860	-1.141	1	
1911	.795	19		1961	-1.277	41	2	1811	-.225	1		1861	-2.850	1	

1912	.826	19	1962	.498	41	2<<
1913	.136	20	1963	-1.392	41	1
1914	.542	20	1964	-.454	41	1
1915	-.540	20	1965	1.331	41	1<<
1916	-2.015	22	1966	.253	42	1<<
1917	-.428	25	1967	-.450	42	1
1918	-.105	25	1968	.681	42	1<<
1919	-.540	25	1969	.306	42	1<<
1920	-.371	25	1970	.092	42	1<<
1921	1.059	25	1971	.920	42	
1922	-.413	25	1972	-1.302	42	
1923	-.071	25	1973	1.129	42	
1924	.036	25	1974	.924	42	1<<
1925	.538	26	1975	.996	41	1<<
1926	.684	27	1976	-.868	41	
1927	.709	30	1977	-2.114	41	

1812	-1.153	1	1862	.007	2	
1813	-.928	1	1863	-.473	2	
1814	1.026	1	1864	1.311	2	
1815	1.575	1	1865	-.106	2	
1816	1.062	1	1866	1.469	3	
1817	-.016	1	1867	.581	3	
1818	.720	1	1868	.201	3	
1819	1.177	1	1869	.399	3	
1820	.953	1	1870	.278	3	
1821	-.379	1	1871	-3.122	3	
1822	-2.455	1	1872	.635	3	
1823	.312	1	1873	.440	4	
1824	-2.083	1	1874	-1.250	4	
1825	.009	1	1875	-.242	4	
1826	-2.159	1	1876	.362	4	
1827	.564	1	1877	.395	4	

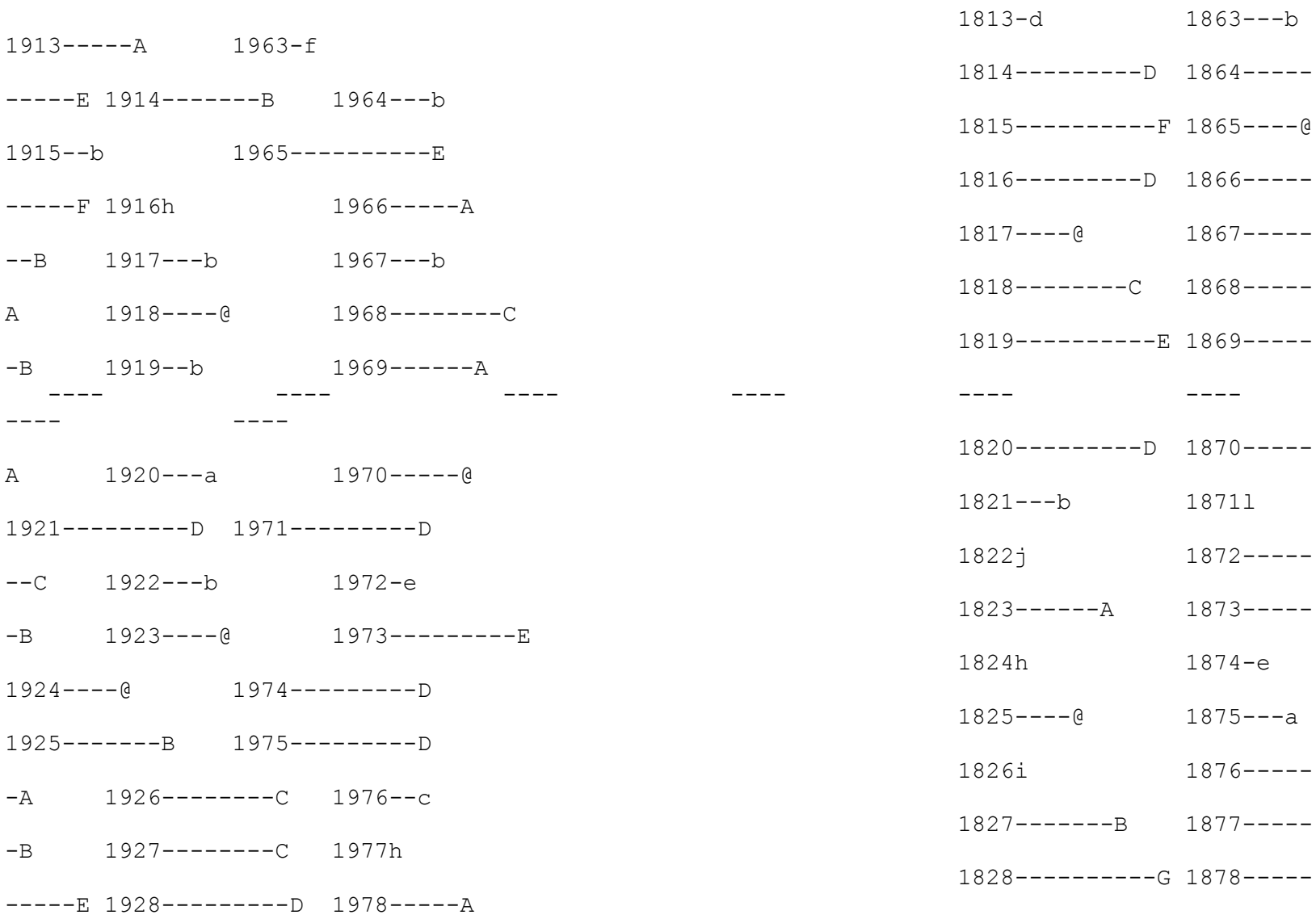
1928	.957	31		1978	.261	41		1828	1.813	1		1878	1.335	4
1929	.997	32		1979	.694	41		1829	-.246	1		1879	-.305	4
1930	.714	33		1980	-.852	41		1830	-1.762	1		1880	-1.187	4
1931	-.716	33		1981	-1.386	41	1	1831	.905	1		1881	-.792	4
1932	-.069	34		1982	.714	41		1832	.131	1		1882	.352	4
1933	-.970	34		1983	1.444	41	1<<	1833	-.661	1		1883	.477	4
1934	-2.957	34		1984	1.077	41	1<<	1834	-.336	1		1884	.035	4
1935	-.540	34		1985	.809	41		1835	1.504	1		1885	1.404	5
1936	-.642	35		1986	.554	41		1836	.594	1		1886	.786	5
1937	.160	35		1987	-.340	40		1837	1.783	1		1887	-.370	5
1938	.587	35		1988	-.493	40		1838	1.762	1		1888	-.441	5
1939	-.137	36		1989	-1.143	40		1839	.247	1		1889	.587	5
1940	-.101	37		1990	-.974	40		1840	.284	1		1890	-.613	5
1941	.810	37		1991	-.709	40	1	1841	.388	1		1891	.489	5
1942	.401	37		1992	-.545	40	1	1842	-1.484	1		1892	.427	6
1943	.821	37		1993	-.699	40	2	1843	.802	1		1893	-.784	7

1944	-.372	37	1994	-.341	40	1<<
1945	.332	37	1995	.862	40	1<<
1946	-.167	37	1996	.034	40	2<<
1947	.841	37	1997	.424	40	
1948	1.011	37	1998	.052	40	1<<
1949	1.222	39	1999	.768	40	2<<

1844	-3.361	1	1894	-.888	7
1845	-.915	1	1895	.226	7
1846	.221	1	1896	-.345	7
1847	-1.164	1	1897	.140	7
1848	.517	1	1898	.315	8
1849	1.681	1	1899	-1.776	8

Year	Value	No Ab		Year	Value	No Ab		Year	Value	No Ab		Year	Value	No Ab		Year	Value	No Ab		Year	Value	No Ab
2000	.058	40	2<<																			
2001	-.258	40	2<<																			
2002	-2.154	40	2																			
2003	.179	39	3<<																			
2004	.728	39	2<<																			
2005	1.204	39	2<<																			
2006	.164	39	5<<																			
2007	.626	38	3<<																			
2008	-.825	38	3																			
2009	.661	38	1<<																			
2010	-.502	38																				
2011	.563	36																				
2012	-.651	35																				
2013	-1.187	34																				
2014	1.017	32																				
2015	1.014	17																				

```
 ------------------------------------------------------------------------------------------
----------------------------------------
   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel
value  Year Rel value  Year Rel value
                                                                   1800----@       1850-----
----E  1900----a       1950--c
                                                                   1801-----A      1851m
1901-----A      1951h
                                                                   1802---------D  1852-----
A      1902g           1952-----A
                                                                   1803-------C    1853-----
-B     1903------B     1953--------C
                                                                   1804--------C   1854-----
---C   1904--c         1954h
                                                                   1805-------B    1855-----
A      1905--c         1955------A
                                                                   1806--b         1856-e
1906-------C    1956-e
                                                                   1807----------E 1857-----
A      1907----------E 1957---------D
                                                                   1808----------E 1858-----
----D  1908-----A      1958--------C
                                                                   1809--b         1859-----
--B    1909------A     1959---a
   ----            ----            ----            ----            ----            ----
----            ----
                                                                   1810-f          1860-e
1910---a        1960------A
                                                                   1811---a        1861k
1911--------C   1961-e
                                                                   1812-e          1862----@
1912--------C   1962-------B
```


1913-----A
1963-f
-----E
1914-------B
1964---b
1915--b
1965----------E
-----F
1916h
1966-----A
--B
1917---b
1967---b
A
1918----@
1968--------C
-B
1919--b
1969------A
1920---a
1970-----@
1921---------D
1971---------D
--C
1922---b
1972-e
-B
1923----@
1973---------E
1924----@
1974---------D
1925-------B
1975---------D
-A
1926--------C
1976--c
-B
1927--------C
1977h
-----E
1928---------D
1978-----A
1813-d
1863---b
1814---------D
1864-----
1815----------F
1865----@
1816---------D
1866-----
1817----@
1867-----
1818--------C
1868-----
1819----------E
1869-----
1820---------D
1870-----
1821---b
1871l
1822j
1872-----
1823------A
1873-----
1824h
1874-e
1825----@
1875---a
1826i
1876-----
1827-------B
1877-----
1828----------G
1878-----

```
1929---------D  1979--------C
   ----             ----             ----             ----
----             ----

1930--------C   1980--c

1931--c         1981-f

-A     1932----@       1982--------C

-B     1933-d          1983----------F

19341           1984---------D

-----F 1935--b          1985--------C

---C   1936--c          1986-------B

1937-----A      1987---a

1938-------B    1988--b

--B    1939----a       1989-e
   ----             ----             ----             ----
----             ----

1940----@       1990-d

--B    1941--------C   1991--c

-B     1942------B     1992--b

1943--------C   1993--c
```

```
1829---a        1879---a
----             ----

1830g           1880-e

1831---------D  1881--c

1832-----A      1882-----

1833--c         1883-----

1834---a        1884----@

1835----------F 1885-----

1836-------B    1886-----

1837----------G 1887---a

1838----------G 1888---b

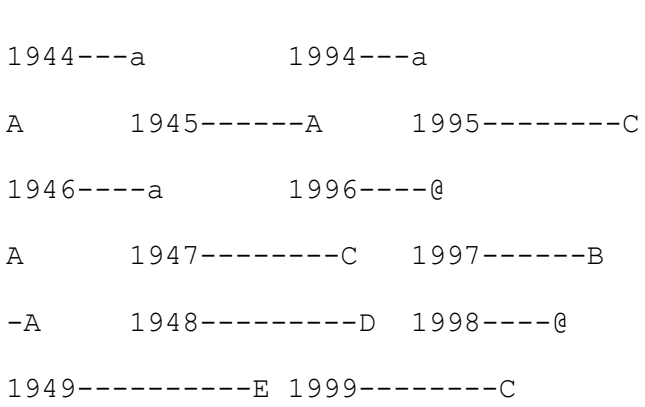
1839-----A      1889-----
----             ----

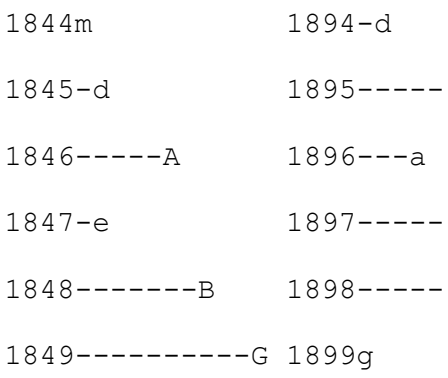
1840-----A      1890--b

1841------B     1891-----

1842-f          1892-----

1843--------C   1893--c
```


1944---a
1994---a
A
1945------A
1995--------C
1946----a
1996----@
A
1947--------C
1997------B
-A
1948---------D
1998----@
1949----------E
1999--------C


1844m
1894-d
1845-d
1895-----
1846-----A
1896---a
1847-e
1897-----
1848-------B
1898-----
1849----------G
1899g

```
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----------------------------------------
   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel
value  Year Rel value  Year Rel value
   2000----@
   2001---a
   2002i
   2003-----A
   2004--------C
   2005----------E
   2006-----A
   2007-------C
   2008--c
   2009-------C
   ----            ----            ----            ----            ----            ----
----            ----
   2010--b
   2011-------B
   2012--c
   2013-e
   2014---------D
   2015---------D




   ----            ----            ----            ----            ----            ----
----            ----
```


PART 5: CORRELATION OF SERIES BY SEGMENTS: cores8 omitted
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Correlations of 50-year dated segments, lagged 25 years
Flags: A = correlation under .3281 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
1	41_32Aab	1909 2014			.68	.75	.76	.78
2	4235Aabc	1898 2014		.75	.76	.85	.87	.83
3	D1_2_1B	1907 2014			.73	.73	.77	.77
4	1_33Aab	1928 2014				.76	.84	.82
5	3_3_1_A	1885 2013		.69	.73	.85	.84	.86
6	3_32Aab	1900 2014			.40	.78	.86	.74
7	4131Aabc	1936 2014				.68	.83	.80
8	D1_52A	1930 2010				.39	.40	.69
9	D1_21C	1906 2014			.78	.80	.69	.66
10	D3_33A	1927 2010				.57	.74	.59
11	D3_33B	1929 2006				.24B	.47	.53
12	42_35B	1954 2014					.80	.72
13	BC	1904 2015			.66	.74	.85	.78
14	L1 A	1932 2015				.79	.88	.85
15	S&L 1	1939 2014				.57	.55	.53
16	L3	1966 2015					.66	
17	S4 B	1892 2015		.65	.75	.76	.73	.78
18	S&L 4A	1949 2015				.71	.70	.59
19	S&L 4B	1949 2002				.83	.83	.68
20	S&L 4C	1951 2013					.79	.55
21	L 4A	1925 2015				.84	.89	.71
22	L 4B	1893 2015		.59	.65	.84	.91	.74

23	L5	1873	2015	.56	.58	.73	.73	.80	.74
24	OK 1A	1917	2015			.83	.88	.89	.91
25	OK 1B	1910	2015			.82	.93	.92	.92
26	Basecamp	1904	2015			.63	.75	.86	.78
27	S4A	1904	1986			.54	.71	.63	
28	Pb1A	1917	2015			.71	.78	.67	.64
29	Pb1B	1927	2015				.81	.76	.71
30	S&L5A	1940	1974				.75		
31	S&L5B	1927	2015				.77	.69	.43
32	S&L6A	1901	2015			.79	.88	.89	.90
33	S&L6B	1926	2015				.71	.71	.75
34	S&L6C	1904	2014			.74	.66	.65	.67
35	S&L6D	1908	2015			.29A	.42	.43	.69
36	S5B	1913	2011			.34B	.44	.66	.48
37	34Aab	1800	2014	.23B	.40	.62	.85	.79	.67
38	4133Aab	1916	2012			.79	.85	.79	.66
39	4234B	1862	2014	.65	.78	.78	.82	.79	.58
40	4234A	1917	2014			.79	.81	.70	.56
41	D135Aab	1866	2014	.26B	.14B	.19B	.40	.50	.53
42	41_33Bab	1916	2014			.77	.84	.78	.74

```
 PART 6:  POTENTIAL PROBLEMS: cores8 omitted
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 For each series with potential problems the following diagnostics may appear:

 [A] Correlations with master dating series of flagged  50-year segments of series filtered
with  32-year spline,
     at every point from ten years earlier (-10) to ten years later (+10) than dated

 [B] Effect of those data values which most lower or raise correlation with master series

 [C] Year-to-year changes very different from the mean change in other series

 [D] Absent rings (zero values)

 [E] Values which are statistical outliers from mean for the year

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 41_32Aab  1909 to  2014     106 years
Series   1

 [B] Entire series, effect on correlation (  .732) is:
       Lower   1972  -.010   1910  -.010   1928  -.010   1958  -.008  Higher   1934   .024
1963   .010   1977   .008   1965   .007


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 4235Aabc  1898 to  2014     117 years
Series   2

 [B] Entire series, effect on correlation (  .809) is:
      Lower   2008  -.018   1944  -.011   1939  -.006   1915  -.006  Higher   1934   .016
2002   .010   1902   .007   1963   .006

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      2008 +3.2 SD

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 D1_2_1B   1907 to  2014     108 years
Series   3

 [B] Entire series, effect on correlation (  .742) is:
      Lower   1911  -.011   1931  -.010   1967  -.009   1971  -.008  Higher   1954   .020
1977   .008   1916   .006   1983   .005

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1993    -.699      40       2


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 1_33Aab   1928 to  2014      87 years
Series   4

 [B] Entire series, effect on correlation (  .774) is:
      Lower   1930  -.024   2000  -.011   1945  -.009   1950  -.008  Higher   1977   .012
2002   .008   1954   .007   1934   .006
```

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 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1943 +3.0 SD

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 3_3_1_A   1885 to  2013     129 years
Series   5

 [B] Entire series, effect on correlation (  .772) is:
       Lower   1916  -.015   1891  -.010   1889  -.008   1944  -.007  Higher   1934   .021
2002   .011   1977   .007   1902   .007

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1916 +3.3 SD

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 3_32Aab   1900 to  2014     115 years
Series   6

 [B] Entire series, effect on correlation (  .626) is:
       Lower   2003  -.028   1902  -.028   1916  -.026   1907  -.022  Higher   1934   .040
1954   .024   2002   .013   1977   .011

 [D]    1 Absent rings:  Year   Master  N series Absent
                         2003     .179      39       3  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     6   3.0 SD above or -4.5 SD below mean for year
       1902 +4.0 SD;    1907 -4.5 SD;    1916 +4.4 SD;    1917 +3.4 SD;    1934 -5.8 SD;
2003 -5.9 SD
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 4131Aabc  1936 to  2014      79 years
Series   7

 [B] Entire series, effect on correlation (  .699) is:
       Lower   1944  -.060   1936  -.028   1938  -.011   2003  -.010  Higher   1951   .018
1977   .016   1965   .011   1972   .010

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1936 +4.6 SD;    1944 -6.5 SD

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 D1_52A    1930 to  2010      81 years
Series   8

 [B] Entire series, effect on correlation (  .546) is:
       Lower   1958  -.099   1963  -.028   1954  -.017   1962  -.016  Higher   2002   .037
1983   .013   1934   .012   1977   .011

 [D]    5 Absent rings:  Year   Master  N series Absent
                         1958     .743      41       2  >> WARNING:  Ring is not usually
narrow
                         1959    -.331      41       2  >> WARNING:  Ring is not usually
narrow
                         1960     .315      41       2  >> WARNING:  Ring is not usually
narrow
                         1961   -1.277      41       2
                         1962     .498      41       2  >> WARNING:  Ring is not usually
narrow
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 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1951 +3.1 SD;    1954 +3.3 SD;    1958 -5.0 SD

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 D1_21C    1906 to  2014     109 years
Series   9

 [B] Entire series, effect on correlation (  .714) is:
       Lower   1981  -.017   1995  -.016   2002  -.013   1963  -.011  Higher   1934   .028
1954   .015   1977   .009   1916   .006

 [D]    3 Absent rings:  Year   Master  N series Absent
                         1994    -.341      40       1  >> WARNING:  Ring is not usually
narrow
                         1995     .862      40       1  >> WARNING:  Ring is not usually
narrow
                         1996     .034      40       2  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1916 -6.7 SD;    1981 +3.4 SD

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 D3_33A    1927 to  2010      84 years
Series  10

 [B] Entire series, effect on correlation (  .512) is:
       Lower   1929  -.051   1931  -.028   1997  -.023   1942  -.019  Higher   1954   .055
1972   .027   1977   .026   1965   .013
```

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 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1929 -6.8 SD;    1931 +3.3 SD;    1940 +3.2 SD;    1954 -4.6 SD

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 D3_33B    1929 to  2006      78 years
Series  11

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3
+4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
---  ---  ---  ---  ---  ---  ---
    1929 1978    9    .03  .20  .33  .14 -.08 -.01 -.20 -.13 -.13 -.44  .24|-.15  .12  .02
.05  .23 -.20 -.16  .05  .37* .01

 [B] Entire series, effect on correlation (  .311) is:
       Lower   1934  -.044   1941  -.044   1942  -.032   1981  -.016  Higher   2002   .049
1972   .044   1954   .029   1965   .024
     1929 to 1978 segment:
       Lower   1941  -.059   1934  -.059   1942  -.041   1933  -.021  Higher   1972   .068
1954   .045   1965   .039   1976   .034

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1934 +5.8 SD;    1940 +3.4 SD;    1964 +3.7 SD;    1977 +3.1 SD

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 42_35B    1954 to  2014      61 years
Series  12

 [B] Entire series, effect on correlation (  .768) is:
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       Lower   2008  -.037   2000  -.020   1979  -.008   2003  -.007  Higher   1972   .014
1963   .012   2002   .012   1957   .007

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2008 +3.6 SD

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 BC        1904 to  2015     112 years
Series  13

 [B] Entire series, effect on correlation (  .726) is:
       Lower   1934  -.013   2002  -.011   2006  -.008   1949  -.008  Higher   1972   .009
1963   .007   1965   .007   1977   .006

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1916 -5.1 SD

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 L1 A      1932 to  2015      84 years
Series  14

 [B] Entire series, effect on correlation (  .790) is:
       Lower   1933  -.023   1944  -.009   2003  -.008   2007  -.006  Higher   2002   .011
1977   .010   1951   .009   1972   .009

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1933 +3.3 SD

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 S&L 1     1939 to  2014      76 years
Series  15

 [B] Entire series, effect on correlation (  .628) is:
       Lower   1983  -.060   1950  -.025   1984  -.024   1975  -.014  Higher   2002   .035
1954   .034   1951   .017   1963   .014

 [D]    3 Absent rings:  Year   Master  N series Absent
                         1981   -1.386      41       1
                         1983    1.444      41       1  >> WARNING:  Ring is not usually
narrow
                         1984    1.077      41       1  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1950 +3.0 SD;    1983 -5.2 SD;    1984 -4.6 SD

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 L3        1966 to  2015      50 years
Series  16

 [B] Entire series, effect on correlation (  .659) is:
       Lower   1972  -.063   1976  -.034   1988  -.023   2010  -.017  Higher   1977   .044
2002   .035   1981   .016   1980   .014

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1972 +3.8 SD;    1988 +3.2 SD

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 S4 B      1892 to  2015     124 years
Series  17

 [B] Entire series, effect on correlation (  .705) is:
       Lower   1899  -.031   1900  -.030   1917  -.013   1989  -.009  Higher   1934   .029
1954   .014   2002   .012   1951   .011

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1899 1900  -4.1 SD

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1895 +3.7 SD;    1899 +4.4 SD;    1917 +3.9 SD;    1934 -4.7 SD

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 S&L 4A    1949 to  2015      67 years
Series  18

 [B] Entire series, effect on correlation (  .618) is:
       Lower   1958  -.032   2006  -.024   2007  -.024   1981  -.020  Higher   1977   .024
1972   .023   1963   .018   1961   .013

 [D]    3 Absent rings:  Year   Master  N series Absent
                         2006     .164      39       5  >> WARNING:  Ring is not usually
narrow
                         2007     .626      38       3  >> WARNING:  Ring is not usually
narrow
                         2008    -.825      38       3

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1981 +3.0 SD;    2001 +3.1 SD;    2002 +3.0 SD;    2007 -4.8 SD
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 S&L 4B    1949 to  2002      54 years
Series  19

 [B] Entire series, effect on correlation (  .676) is:
       Lower   2002  -.152   1960  -.014   1950  -.013   1981  -.008  Higher   1954   .032
1977   .023   1963   .019   1972   .018

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2002 +7.2 SD

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 S&L 4C    1951 to  2013      63 years
Series  20

 [B] Entire series, effect on correlation (  .618) is:
       Lower   2013  -.042   2004  -.034   2002  -.027   2012  -.019  Higher   1951   .022
1963   .016   1983   .013   1977   .012

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1954 +3.5 SD;    2013 +4.9 SD

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 L 4A      1925 to  2015      91 years
Series  21

 [B] Entire series, effect on correlation (  .783) is:
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       Lower   2006  -.054   1933  -.007   1972  -.007   2002  -.007  Higher   1934   .027
1977   .008   1963   .006   1973   .005

 [D]    1 Absent rings:  Year   Master  N series Absent
                         2006     .164      39       5  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2006 -5.8 SD

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 L 4B      1893 to  2015     123 years
Series  22

 [B] Entire series, effect on correlation (  .705) is:
       Lower   1915  -.032   2006  -.031   1894  -.020   1896  -.013  Higher   1916   .012
1951   .010   1934   .010   1977   .009

 [D]    1 Absent rings:  Year   Master  N series Absent
                         2006     .164      39       5  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1894 +4.2 SD;    1915 -7.1 SD;    2006 -5.2 SD

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 L5        1873 to  2015     143 years
Series  23

 [B] Entire series, effect on correlation (  .669) is:
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       Lower   1884  -.033   1961  -.018   1881  -.017   1939  -.016  Higher   1954   .015
1934   .011   1899   .010   1902   .008

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1881 -5.4 SD;    1884 -4.7 SD;    1961 +4.2 SD;    2004 +3.4 SD

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 OK 1A     1917 to  2015      99 years
Series  24

 [B] Entire series, effect on correlation (  .868) is:
       Lower   1918  -.009   1990  -.008   1959  -.008   1919  -.005  Higher   1934   .015
2002   .008   1977   .006   1951   .005

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1918 +3.1 SD

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 OK 1B     1910 to  2015     106 years
Series  25

 [B] Entire series, effect on correlation (  .868) is:
       Lower   1915  -.014   1921  -.012   1910  -.007   1916  -.007  Higher   1934   .011
2002   .007   1954   .006   1951   .004


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 Basecamp  1904 to  2015     112 years
Series  26

 [B] Entire series, effect on correlation (  .715) is:
       Lower   1909  -.013   1949  -.013   1934  -.011   2002  -.009  Higher   1972   .009
1963   .009   1965   .007   1983   .005

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1916 -5.1 SD

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 S4A       1904 to  1986      83 years
Series  27

 [B] Entire series, effect on correlation (  .568) is:
       Lower   1974  -.041   1916  -.041   1908  -.025   1975  -.019  Higher   1934   .075
1954   .028   1951   .014   1973   .011

 [D]    2 Absent rings:  Year   Master  N series Absent
                         1974     .924      42       1  >> WARNING:  Ring is not usually
narrow
                         1975     .996      41       1  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1908 -5.1 SD;    1916 +4.7 SD;    1934 -5.6 SD;    1975 -4.5 SD

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 Pb1A      1917 to  2015      99 years
Series  28
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 [B] Entire series, effect on correlation (  .676) is:
      Lower   1977  -.031   1917  -.019   1993  -.013   1931  -.011  Higher   1934   .026
2002   .022   1972   .013   1954   .008

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
      1977 +4.0 SD;    1993 +3.4 SD

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 Pb1B      1927 to  2015      89 years
Series  29

 [B] Entire series, effect on correlation (  .758) is:
      Lower   1940  -.019   1993  -.019   1929  -.015   1992  -.011  Higher   1934   .031
2002   .014   1954   .010   1977   .008

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1993 +3.8 SD

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 S&L5A     1940 to  1974      35 years
Series  30

 [B] Entire series, effect on correlation (  .749) is:
      Lower   1950  -.029   1945  -.028   1964  -.023   1956  -.013  Higher   1951   .032
1963   .027   1954   .023   1957   .010


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 S&L5B     1927 to  2015      89 years
Series  31

 [B] Entire series, effect on correlation (  .559) is:
      Lower   2002  -.066   1991  -.023   1992  -.020   1927  -.019  Higher   1954   .021
1963   .016   1977   .016   1961   .012

 [D]    3 Absent rings:  Year   Master  N series Absent
                         1991    -.709      40       1
                         1992    -.545      40       1
                         1993    -.699      40       2

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
      1991 -5.3 SD;    1992 -5.5 SD;    1993 -5.3 SD;    2002 +6.2 SD

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 S&L6A     1901 to  2015     115 years
Series  32

 [B] Entire series, effect on correlation (  .855) is:
      Lower   1964  -.012   1902  -.011   1930  -.005   1908  -.004  Higher   1934   .013
1954   .010   2002   .006   1916   .005


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 S&L6B     1926 to  2015      90 years
Series  33

 [B] Entire series, effect on correlation (  .728) is:
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```
       Lower   1991  -.022   1939  -.017   1937  -.016   1950  -.012  Higher   2002   .017
1954   .016   1951   .012   1934   .012

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1991 +3.9 SD;    1992 +3.8 SD

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 S&L6C     1904 to  2014     111 years
Series  34

 [B] Entire series, effect on correlation (  .703) is:
       Lower   1972  -.016   1927  -.010   1968  -.010   1963  -.009  Higher   1934   .014
1954   .008   1977   .007   1965   .007

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2002 -6.0 SD

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 S&L6D     1908 to  2015     108 years
Series  35

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3
+4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
---  ---  ---  ---  ---  ---  ---
    1908 1957    0   -.15 -.19 -.14 -.09 -.05 -.09  .03  .12  .12  .29  .29* .20 -.01 -.14 -
.06 -.09 -.05 -.12 -.08 -.04 -.12

 [B] Entire series, effect on correlation (  .456) is:
```

```
       Lower   1917  -.056   1931  -.022   1972  -.015   1965  -.013  Higher   2002   .036
1934   .020   1950   .012   1973   .009
     1908 to 1957 segment:
       Lower   1917  -.093   1931  -.038   1957  -.019   1937  -.019  Higher   1934   .066
1950   .042   1933   .021   1948   .019

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1916 1917  -5.4 SD

 [D]   20 Absent rings:  Year   Master  N series Absent
                         1951   -1.958      40       1
                         1952     .285      40       1  >> WARNING:  Ring is not usually
narrow
                         1953     .689      40       1  >> WARNING:  Ring is not usually
narrow
                         1954   -2.035      41       1
                         1955     .321      41       1  >> WARNING:  Ring is not usually
narrow
                         1956   -1.184      41       1
                         1957     .998      41       1  >> WARNING:  Ring is not usually
narrow
                         1958     .743      41       2  >> WARNING:  Ring is not usually
narrow
                         1959    -.331      41       2  >> WARNING:  Ring is not usually
narrow
                         1960     .315      41       2  >> WARNING:  Ring is not usually
narrow
                         1961   -1.277      41       2
                         1962     .498      41       2  >> WARNING:  Ring is not usually
narrow
                         1963   -1.392      41       1
                         1964    -.454      41       1
                         1965    1.331      41       1  >> WARNING:  Ring is not usually
narrow
```

```
                          1966     .253      42       1  >> WARNING:  Ring is not usually
narrow
                          1967    -.450      42       1
                          1968     .681      42       1  >> WARNING:  Ring is not usually
narrow
                          1969     .306      42       1  >> WARNING:  Ring is not usually
narrow
                          1970     .092      42       1  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     5   3.0 SD above or -4.5 SD below mean for year
       1913 +3.1 SD;    1916 +3.9 SD;    1917 -7.2 SD;    1931 +4.2 SD;    1972 +4.0 SD

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 S5B       1913 to  2011      99 years
Series  36

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3
+4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
---  ---  ---  ---  ---  ---  ---
    1913 1962    1   -.05 -.25 -.26  .00 -.17  .11 -.06 -.15  .17 -.07  .34| .43* .01 -.10 -
.01  .19 -.17 -.05 -.13 -.19 -.10

 [B] Entire series, effect on correlation (  .397) is:
       Lower   1934  -.046   1977  -.022   1949  -.022   2004  -.020  Higher   1951   .020
1972   .018   1954   .017   2002   .014
     1913 to 1962 segment:
       Lower   1934  -.083   1949  -.040   1938  -.031   1931  -.023  Higher   1951   .041
1954   .037   1950   .015   1956   .014

 [C] Year-to-year changes diverging by over 4.0 std deviations:
```

```
       1933 1934   5.7 SD

 [E] Outliers     5   3.0 SD above or -4.5 SD below mean for year
       1933 -7.8 SD;    1934 +5.7 SD;    1977 +4.3 SD;    1981 +3.0 SD;    1992 +3.5 SD

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 34Aab     1800 to  2014     215 years
Series  37

 [*] Early part of series cannot be checked from 1800 to 1861 -- not matched by another
series

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3
+4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
---  ---  ---  ---  ---  ---  ---
    1862 1911   -3   -.27  .08  .14 -.14  .04 -.05 -.09  .27* .11 -.25  .23| .02 -.02 -.04 -
.09 -.05  .14 -.15  .13 -.15 -.09

 [B] Entire series, effect on correlation (  .491) is:
       Lower   1871  -.049   1881  -.031   1873  -.017   1862  -.013  Higher   1954   .018
2002   .015   1934   .014   1902   .011
     1862 to 1911 segment:
       Lower   1871  -.073   1881  -.061   1873  -.030   1862  -.026  Higher   1899   .059
1902   .038   1866   .026   1885   .021

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1870 1871   4.4 SD

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1800    -.037       1       1  >> WARNING:  Ring is not usually
narrow
```

```
   >> WARNING:  First ring in series is ABSENT

 [E] Outliers     9   3.0 SD above or -4.5 SD below mean for year
       1800 -5.0 SD;    1862 +3.4 SD;    1867 +3.4 SD;    1871 +6.3 SD;    1881 +7.2 SD;
1899 -6.5 SD;    1916 +3.3 SD;
       1917 +3.2 SD;    1993 +4.5 SD

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 4133Aab   1916 to  2012      97 years
Series  38

 [B] Entire series, effect on correlation (  .710) is:
       Lower   2002  -.020   1999  -.014   2012  -.014   1981  -.011  Higher   1977   .014
1916   .014   1972   .012   1954   .010


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 4234B     1862 to  2014     153 years
Series  39

 [B] Entire series, effect on correlation (  .678) is:
       Lower   1999  -.026   1862  -.017   1863  -.016   1874  -.015  Higher   1871   .024
1954   .011   1916   .010   1902   .009

 [D]   11 Absent rings:  Year   Master  N series Absent
                         1999     .768      40       2  >> WARNING:  Ring is not usually
narrow
                         2000     .058      40       2  >> WARNING:  Ring is not usually
narrow
```

```
                        2001    -.258      40       2  >> WARNING:  Ring is not usually
narrow
                        2002   -2.154      40       2
                        2003     .179      39       3  >> WARNING:  Ring is not usually
narrow
                        2004     .728      39       2  >> WARNING:  Ring is not usually
narrow
                        2005    1.204      39       2  >> WARNING:  Ring is not usually
narrow
                        2006     .164      39       5  >> WARNING:  Ring is not usually
narrow
                        2007     .626      38       3  >> WARNING:  Ring is not usually
narrow
                        2008    -.825      38       3
                        2009     .661      38       1  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1864 +3.2 SD;    1874 -4.7 SD;    1891 +3.2 SD

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 4234A     1917 to  2014      98 years
Series  40

 [B] Entire series, effect on correlation (  .667) is:
       Lower   1998  -.038   2005  -.014   1999  -.011   1991  -.010  Higher   1954   .027
1934   .020   1972   .014   1963   .013

 [D]   11 Absent rings:  Year   Master  N series Absent
                        1998     .052      40       1  >> WARNING:  Ring is not usually
narrow
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```
                        1999     .768      40       2  >> WARNING:  Ring is not usually
narrow
                        2000     .058      40       2  >> WARNING:  Ring is not usually
narrow
                        2001    -.258      40       2  >> WARNING:  Ring is not usually
narrow
                        2002   -2.154      40       2
                        2003     .179      39       3  >> WARNING:  Ring is not usually
narrow
                        2004     .728      39       2  >> WARNING:  Ring is not usually
narrow
                        2005    1.204      39       2  >> WARNING:  Ring is not usually
narrow
                        2006     .164      39       5  >> WARNING:  Ring is not usually
narrow
                        2007     .626      38       3  >> WARNING:  Ring is not usually
narrow
                        2008    -.825      38       3


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 D135Aab   1866 to  2014     149 years
Series  41

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3
+4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
---  ---  ---  ---  ---  ---  ---
    1866 1915    3    .16  .13  .09 -.26  .17 -.33 -.01 -.18 -.15  .05  .26|-.07  .03  .32*
.02  .00  .09  .03  .00  .05 -.04
    1875 1924   -9    .02  .26*-.13 -.25  .04 -.26 -.01 -.13 -.08  .12  .14| .08  .09  .17
.07  .13  .14  .20 -.12 -.03 -.17
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    1900 1949   -2   -.14 -.04 -.10 -.40 -.26 -.18 -.02 -.05  .28* .24  .19| .25  .17  .10
.18 -.18  .05 -.14 -.17  .00 -.31

 [B] Entire series, effect on correlation (  .382) is:
       Lower   1934  -.027   1883  -.026   1905  -.016   1887  -.014  Higher   1871   .038
1954   .020   1972   .018   1951   .016
     1866 to 1915 segment:
       Lower   1883  -.065   1905  -.041   1887  -.038   1874  -.025  Higher   1871   .177
1899   .037   1866   .031   1878   .022
     1875 to 1924 segment:
       Lower   1883  -.090   1905  -.049   1887  -.046   1884  -.027  Higher   1899   .066
1878   .038   1916   .032   1880   .028
     1900 to 1949 segment:
       Lower   1934  -.069   1905  -.049   1935  -.030   1931  -.021  Higher   1916   .038
1902   .029   1933   .025   1941   .025

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1934 1935  -4.6 SD

 [E] Outliers     6   3.0 SD above or -4.5 SD below mean for year
       1871 -5.5 SD;    1874 +3.4 SD;    1887 +4.0 SD;    1905 +5.2 SD;    1934 +5.4 SD;
1971 +3.7 SD

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 41_33Bab  1916 to  2014      99 years
Series  42

 [B] Entire series, effect on correlation (  .747) is:
       Lower   1996  -.060   1917  -.017   1921  -.008   1944  -.007  Higher   1934   .015
1972   .009   1977   .007   1965   .007

 [D]    1 Absent rings:  Year   Master  N series Absent
```

```
                          1996     .034      40       2  >> WARNING:  Ring is not usually
narrow

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1917 +4.2 SD;    1996 -7.3 SD

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PART 7: DESCRIPTIVE STATISTICS: cores8 omitted
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Seq	Series	Interval		No. Years	No. Segmt	No. Flags	Corr with Master	Unfiltered Mean msmt	Unfiltered Max msmt	Unfiltered Std dev	Unfiltered Auto corr	Filtered Mean sens	Filtered Max value	Filtered Std dev	Filtered Auto corr	AR ()
1	41_32Aab	1909	2014	106	4	0	.732	2.97	7.39	1.349	.557	.377	2.12	.461	.021	1
2	4235Aabc	1898	2014	117	5	0	.809	1.95	5.54	1.225	.784	.421	2.00	.442	-.035	1
3	D1_2_1B	1907	2014	108	4	0	.742	1.25	6.19	1.048	.848	.454	2.09	.405	.013	1
4	1_33Aab	1928	2014	87	3	0	.774	2.53	10.34	1.360	.598	.353	2.06	.350	-.030	1
5	3_3_1_A	1885	2013	129	5	0	.772	1.54	4.53	.985	.897	.310	2.03	.357	-.020	1
6	3_32Aab	1900	2014	115	4	0	.626	1.91	4.21	.938	.746	.311	1.80	.253	-.012	1
7	4131Aabc	1936	2014	79	3	0	.699	3.03	8.12	1.355	.702	.281	1.92	.333	-.037	1
8	D1_52A	1930	2010	81	3	0	.546	2.34	4.68	1.140	.724	.287	2.06	.362	.017	1
9	D1_21C	1906	2014	109	4	0	.714	1.55	5.03	1.071	.807	.416	1.97	.341	.033	1
10	D3_33A	1927	2010	84	3	0	.512	1.21	2.68	.705	.834	.308	1.86	.338	-.055	1

11	D3_33B	1929	2006	78	3	1	.311	.51	1.82	.406	.781	.379	2.07
.449	.027	2											
12	42_35B	1954	2014	61	2	0	.768	1.44	3.73	.893	.488	.540	2.05
.536	-.133	1											
13	BC	1904	2015	112	4	0	.726	2.28	5.32	1.032	.626	.321	1.96
.324	-.017	1											
14	L1 A	1932	2015	84	3	0	.790	1.92	4.07	.918	.590	.433	1.91
.388	.002	1											
15	S&L 1	1939	2014	76	3	0	.628	1.87	5.31	1.119	.580	.456	1.94
.365	-.036	1											
16	L3	1966	2015	50	1	0	.659	2.98	4.53	.973	.548	.278	1.88
.444	.043	1											
17	S4 B	1892	2015	124	5	0	.705	1.28	3.13	.634	.711	.389	1.94
.310	.008	1											
18	S&L 4A	1949	2015	67	3	0	.618	.66	1.49	.394	.716	.432	2.02
.530	.022	1											
19	S&L 4B	1949	2002	54	3	0	.676	.72	1.58	.398	.758	.356	2.20
.451	-.054	1											
20	S&L 4C	1951	2013	63	2	0	.618	.75	1.63	.494	.719	.472	2.00
.508	.026	3											
21	L 4A	1925	2015	91	3	0	.783	1.32	3.31	.699	.738	.358	1.85
.337	-.037	1											
22	L 4B	1893	2015	123	5	0	.705	1.56	3.18	.805	.786	.336	1.90
.347	.031	1											
23	L5	1873	2015	143	6	0	.669	.97	2.32	.434	.565	.341	2.17
.385	-.029	1											
24	OK 1A	1917	2015	99	4	0	.868	1.73	3.40	.762	.577	.385	1.92
.382	-.004	1											
25	OK 1B	1910	2015	106	4	0	.868	1.83	3.74	.785	.614	.360	1.90
.359	-.042	1											
26	Basecamp	1904	2015	112	4	0	.715	2.27	5.33	1.028	.638	.322	1.94
.304	-.013	1											
27	S4A	1904	1986	83	3	0	.568	1.51	3.48	.735	.679	.410	1.86
.282	.028	1											

28	Pb1A	1917	2015	99	4	0	.676	1.44	3.87	.797	.701	.405	2.04
.444	.010	1											
29	Pb1B	1927	2015	89	3	0	.758	1.46	3.65	.786	.616	.424	2.03
.353	.011	1											
30	S&L5A	1940	1974	35	1	0	.749	1.69	2.70	.492	.029	.354	2.15
.562	.013	1											
31	S&L5B	1927	2015	89	3	0	.559	.96	2.13	.543	.590	.433	1.94
.413	.115	1											
32	S&L6A	1901	2015	115	4	0	.855	1.83	3.75	.744	.736	.263	1.90
.326	.001	1											
33	S&L6B	1926	2015	90	3	0	.728	1.28	4.67	.811	.863	.313	1.93
.376	-.027	1											
34	S&L6C	1904	2014	111	4	0	.703	1.40	3.39	.752	.850	.288	1.76
.265	-.018	2											
35	S&L6D	1908	2015	108	4	1	.456	1.32	5.62	1.133	.780	.312	1.96
.305	-.057	1											
36	S5B	1913	2011	99	4	1	.397	.52	1.60	.284	.598	.400	1.85
.293	.001	1											
37	34Aab	1800	2014	215	6	1	.491	1.09	2.96	.656	.798	.349	2.01
.314	-.025	2											
38	4133Aab	1916	2012	97	4	0	.710	1.92	5.64	1.145	.697	.436	2.06
.444	.013	1											
39	4234B	1862	2014	153	6	0	.678	1.23	4.28	.950	.809	.411	2.05
.385	-.030	1											
40	4234A	1917	2014	98	4	0	.667	.55	1.99	.468	.864	.424	2.10
.434	-.014	1											
41	D135Aab	1866	2014	149	6	3	.382	1.19	11.82	1.353	.380	.410	2.14
.278	-.050	1											
42	41_33Bab	1916	2014	99	4	0	.747	1.78	21.65	2.523	.571	.510	1.97
.352	-.023	1											
---	--------	---------	-----	-----	-----	------	-----	-----	-----	-----	-----	---	--
-----	-----	--											
Total or mean:				4187	156	7	.669	1.54	21.65	.898	.694	.374	2.20
.366	-.010												

- = [COFECHA CORE8COF] = -